2mi4

22104-H002-R0-00

CR-134145

FINAL REPORT

FUNCTIONAL REQUIREMENTS FOR ONBOARD MANAGEMENT OF SPACE SHUTTLE CONSUMABLES

(NASA-CR-134145) FUNCTIONAL REQUIREMENTS FOR ONBOARD MANAGEMENT OF SPACE SHUTTLE CONSUMABLES, VOLUME 2, Final Report (TRW Systems Group) ~~145~~ 144 p HC $9.25 CSCL 22B N74-13590 Unclas G3/31 24865

VOLUME II

CONTRACT NAS 9-12944

Prepared For

Mission Planning And Analysis Division
National Aeronautics And Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

TRW
SYSTEMS GROUP

22104-H002-RO-00

FINAL REPORT

FUNCTIONAL REQUIREMENTS FOR ONBOARD MANAGEMENT OF SPACE SHUTTLE CONSUMABLES

VOLUME II

Prepared for
Mission Planning and Analysis Division
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

Contract NAS 9-12944

Prepared by:

P. J. Graf
H. A. Herwig
L. W. Neel

16 November 1973

Approved by: L. W. Neel
L. W. Neel, TRW Study Manager

I

ACKNOWLEDGEMENTS

In addition to those who have worked throughout the study and have been the principal contributors to this report, valuable contributions have been made by numerous other individuals who have provided their ideas and critiques of the information presented herein. All cannot be named, but some of those deserving special mention are listed below:

ECLSS:	M. R. Reumont J. G. Torian
Propulsion:	R. K. M. Seto T. J. Walsh
RCS:	R. D. Miller
FCCS:	R. A. Mintz
Software:	R. F. Jank J. R. Morrison
Instrumentation:	R. A. Kaminskas

CONTENTS

CONTENTS (Concluded)

FIGURES

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Concluded)

TABLES

LIST OF ACRONYMS

AH	Ampere Hour
APU	Auxiliary Power Unit
CM	Consumables Management
CRT	Cathode Ray Tube
DEU	Digital Electronics Unit
ECLSS	Environmental Control and Life Support Subsystem
EOM	End of Mission
EOMR	End-of-Mission Reserves
EPS	Electrical Power Subsystem
ET	External Tank
FC	Fuel Cell
FCCS	Fuel Cell and Cryogenic Storage
FU	Fuel
G&NS	Guidance and Navigation Subsystem
GN&C	Guidance, Navigation and Control
IOB	Input/Output Buffer
I_{sp}	Specific Impulse
K/B	Keyboard
KW	Kilowatts
MDM	Multiplexer/Demultiplexer
MECO	Main Engine Cut-Off
MED	Manual Entry Device
MET	Mission Elapsed Time
MMH	Monomethylhydrazine
MPS	Main Propulsion System
MUX	Multiplexer
O/I	Output/Input
O/F	Oxidizer/Fuel Ratio
OMS	Orbital Maneuvering System
OX	Oxidizer

LIST OF ACRONYMS (Concluded)

PP	Partial Pressure
PSIA	Pounds Per Square Inch Absolute
PVT	Pressure-Volume-Temperature
RCS	Reaction Control Subsystem
RF	Radio Frequency
RIGS	Resonant Infrasonic Gauging System
RMT	Remaining Mission Time
SRM	Solid Rocket Motor
TTBR	Time to Break Redline
TBD	To Be Determined
TTE	Time to Empty
TTF	Time to Full
T/M	Telemetry Measurement
VLV	Valve
XFD	Crossfeed
ρV	Gas Density-Volume

1. INTRODUCTION

This report documents the results of the study conducted under Contract NAS 9-12944, "Functional Requirements for Onboard Management of Space Shuttle Consumables." The study was conducted for the Mission Planning and Analysis Division of the NASA Lyndon B. Johnson Space Center, Houston, Texas, between 3 July 1972 and 16 November 1973.

The overall study program objective was two-fold. The first objective was to define a generalized consumable management concept which is applicable to advanced spacecraft. The second objective was to develop a specific consumables management concept for the Space Shuttle vehicle and to generate the functional requirements for the onboard portion of that concept.

Consumables management is the process of controlling or influencing the usage of expendable materials involved in vehicle subsystem operation. The subsystems and related consumables selected for inclusion in the consumables management system are:

- Propulsion
  - a. Monomethyhydrazine
  - b. Nitrogen Tetroxide
  - c. Liquid Oxygen
  - d. Liquid Hydrogen
- Power Generation
  - a. Cooling Water
  - b. Hydrazine
  - c. Hydrogen
  - d. Oxygen
- Environmental and Life Support
  - a. Ammonia
  - b. Biocide
  - c. Lithium Hydroxide
  - d. Nitrogen
  - e. Oxygen
  - f. Water

The report consists of two volumes. Volume I presents a description of the study activities related to general approaches for developing consumable management, concepts for advanced spacecraft applications, and functional requirements for a Shuttle consumables management concept. Volume II presents a detailed description of the onboard consumables management concept proposed for use on the Space Shuttle.

2. SUMMARY

This report volume presents a detailed description of a viable technique for implementing the proposed shuttle onboard consumables management concept. The technique adapts proven technology from previous spacecraft and aircraft programs for application onboard the shuttle. The proposed onboard software performs many functions similar to Apollo and Skylab ground software programs, and suggested techniques for implementing the consumables management software/crew interface are similar to methods employed on modern aircraft. Therefore, all of the requirements identified for the consumables management system are within the hardware and software state of the art for the Shuttle program.

The management technique described for each subsystem consumable was selected to meet unique requirements imposed by subsystem design and operational features. Prominent features of the shuttle consumables management system are summarized in Table 2-1 and in the descriptions which follow.

Auxiliary Power Units (APU)

The proposed APU onboard consumables management functions include verifying that loaded consumables quantities are adequate for the planned mission and monitoring consumables status to verify that adequate reserves are maintained during the mission. Onboard software provides monitoring and constraints testing of consumables status parameters.

Environmental Control and Life Support Subsystem (ECLSS)

Concepts for ECLSS consumables management includes monitoring, evaluation, and consumables usage planning functions for all consumables except potable water; only monitoring and limit testing functions are performed for water management. The onboard software required to provide inflight replanning of consumables usage is significantly less complicated than that required for prelaunch planning, therefore, the prelaunch planning data is provided by the ground support system.

Fuel Cell and Cryogenics Subsystems (FCCS)

Consumables management functions proposed for the FCCS include full capability for monitoring, evaluating, and predicting cryogen usage. Capability includes inflight prediction and evaluation of cryogen usage for inflight revisions to an existing consumables usage plan. The mandatory nature of FCCS operation and the ability to control cryogen usage places a high priority on providing capability to assure that adequate cryogen quantities are available to complete the mission as planned.

Main Propulsion System/External Tanks (MPS/ET)

The primary onboard function proposed for the MPS/ET consumables management software is to relate propellant quantities to remaining delta-velocity capability. Monitoring and limit testing of parameters is provided in order to present information which is supplementary to Guidance and Navigation information.

Reaction Control System and Orbital Maneuvering System (RCS/OMS)

Management of RCS and OMS propellant usage is necessary because of the essential functions performed by the subsystems. Furthermore, active consumables management can be employed to efficiently utilize the propellant quantities available. Consumables management capability is proposed to provide onboard monitoring, evaluation, and consumables usage planning to support RCS and OMS mission operations.

Table 2-1. Summary of Shuttle Consumables Management Features

Consumable	Onboard Monitoring	Onboard Constraints Tests	Onboard Replanning	Onboard Automatic Replanning
ECLSS Ammonia	X	X	X	X
ECLSS Nitrogen	X	X	X	X
ECLSS Water	X	X	-	-
ECLSS Oxygen	X	X	X	X
ECLSS Lithium Hydroxide	X	X	X	X
FCCS Oxygen	X	X	X	X
FCCS Hydrogen	X	X	X	X
MPS/ET Propellant	X	X	-	-
OMS Propellant	X	X	X	X
RCS Propellant	X	X	X	X
APU Fuel	X	X	-	-
APU Cooling Water	X	X	-	-

3. SHUTTLE CONSUMABLES MANAGEMENT SYSTEM OPERATION OVERVIEW

An overview of the Shuttle consumables management system functions and mission operation features is presented in this section. Also, a discussion is included of the major ground and payload operations interfaces with the consumables management system.

3.1 SHUTTLE CONSUMABLE MANAGEMENT SYSTEM FUNCTIONS

The consumables management role of controlling the usage of subsystem expendables involves four basic functions which must be performed in execution of the consumables management process. The basic functions listed below may be either ground or onboard activities which are performed either manually or automatically.

- Monitoring - the measurement, processing, and observation of subsystem parameters which are indicative of consumables usage. Commonly, the primary parameters of interest are consumable quantity and usage rate measurements, but additional monitoring is frequently required to adequately ascertain consumables usage characteristics.
- Evaluation - the comparison of monitored data to a reference, such as a predicted usage profile, to determine the deviation between actual and reference values.
- Assessment - the determination of causes of deviation of actual usage from predicted conditions, impact of the deviation on the remainder of the mission, and options available to correct for the deviations.
- Corrective Action - the measures taken to correct or control the usage of consumables. Action may include measures such as reconfiguring subsystems, replanning mission activities, or modifying operational procedures all of which may be means to effect control of consumables usage.

Portions of the four basic functions of consumables management were divided into functional units of capability, or functional modules, which were utilized to develop the proposed Shuttle consumables management concept. The functional module definitions follow.

- Monitoring Module - The activities associated with converting and presenting subsystem sensor data to provide consumables status data are included in this module. Consumables status information includes quantity remaining, quantity used, and quantity usage rates.

- Consumables Prediction Module - The functional activities associated with this module include the conversion of mission flight plan data into predicted consumables usage profiles.

- Inflight Consumables Prediction Module - The functional activities of this module are similar to those of the Consumables Prediction Module except that this module provides revised consumables usage predictions based on mission revisions.

- Evaluation Module - The functional task performed within this module includes comparison of actual consumables status with the predicted consumables quantities remaining at the completion of the mission.

- Constraint Module - Testing both measured and calculated consumables parameters against predetermined limit values is the function performed within this module. The specific parameter to be tested for constraint violations is dependent on the particular consumable involved. Typical parameters checked in the constraint module will be consumable usage rates, difference between actual and predicted usage values, and minimum acceptable values for predicted end-of-mission quantities remaining.

These modules are related to the basic consumables management functions as shown in Figure 3-1. The functional modules may be viewed as specific, logical divisions of capability which may be either ground or onboard functions. This modular division of functions is useful in developing an orderly plan for implementation of onboard capability in phases as the Shuttle program progresses from the test phase to the fully operational phase. Furthermore, as the descriptions of the Shuttle Consumables management concept will show, the functional modules were used to describe the software functions performed onboard according to the proposed concept.

3.2 SHUTTLE CONSUMABLES MANAGEMENT SYSTEM OPERATION

The management technique proposed for a majority of the Shuttle consumables utilizes the onboard software to perform the functional module activities. Therefore, the operation of the consumables management system will be described for the fully onboard system, shown in Figure 3-2, and differences from this description will be noted in descriptions of each subsystem concept in Section 4.

The consumable management system consists of five functional modules exercised by a sequencer routine. The modules include the following:

- o Consumables Prediction Module
- o Monitoring Module
- o Evaluation Module
- o Constraints Module
- o Inflight Consumables Prediction Module

The sequencer calls the individual modules in response to either ground, preprogrammed software, or crew commands. The calling order for the modules is determined by selection of a major program sequence which includes 1.) prelaunch analysis, 2.) inflight monitoring and evaluation, and 3.) inflight consumables prediction.

The following discussions of the consumables management system is divided into operations for preflight, inflight, and postflight periods. Operations during these periods requires interfaces with the ground mission planning and scheduling system, ground checkout system, and payload support systems.

3.2.1 Prelaunch Consumables Management System Operation

The consumables management system prelaunch operation cycle starts with the loading of mission class data and vehicle particular data in the onboard software. These data will have been previously generated from the ground mission planning and scheduling systems. Included within these data are such items as a mission activity timeline, trajectory parameters, the mission redline and constraints data which are both consumable and subsystem related, and subsystem model data for the particular Shuttle vehicle being used. The subsystem model data would include degradation trends associated with subsystem performance for equipment such as the fuel cells and rocket engines.

The onboard mission information management software will process the mission activity timeline into consumable event timelines for use by the consumables management system. The consumable Prediction Module will utilize the individual consumable event timelines to determine the consumable requirements for the mission specified by the activity timeline.

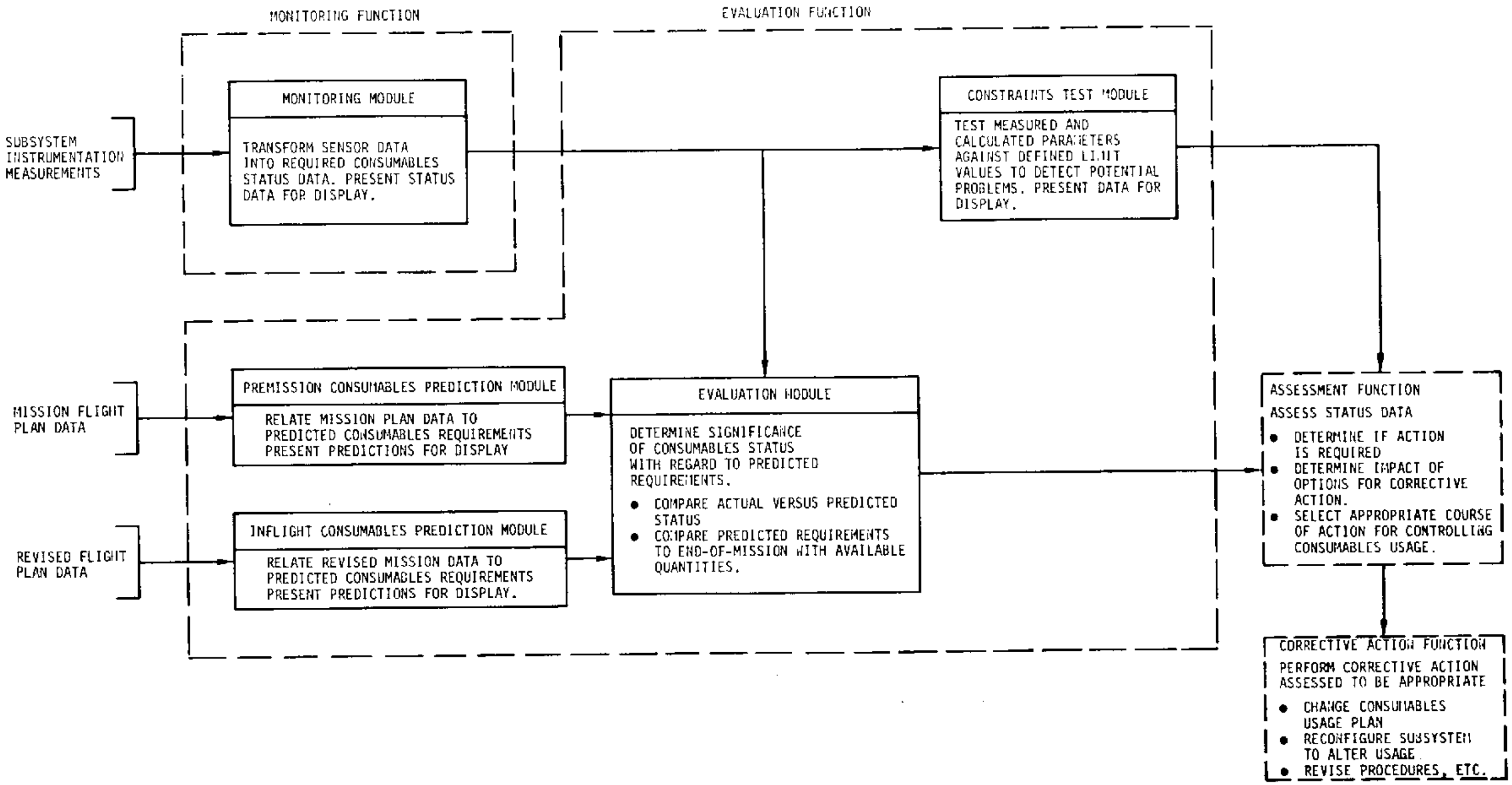


Figure 3-1. Relationship of Consumables Management Functions to the Defined Functional Modules

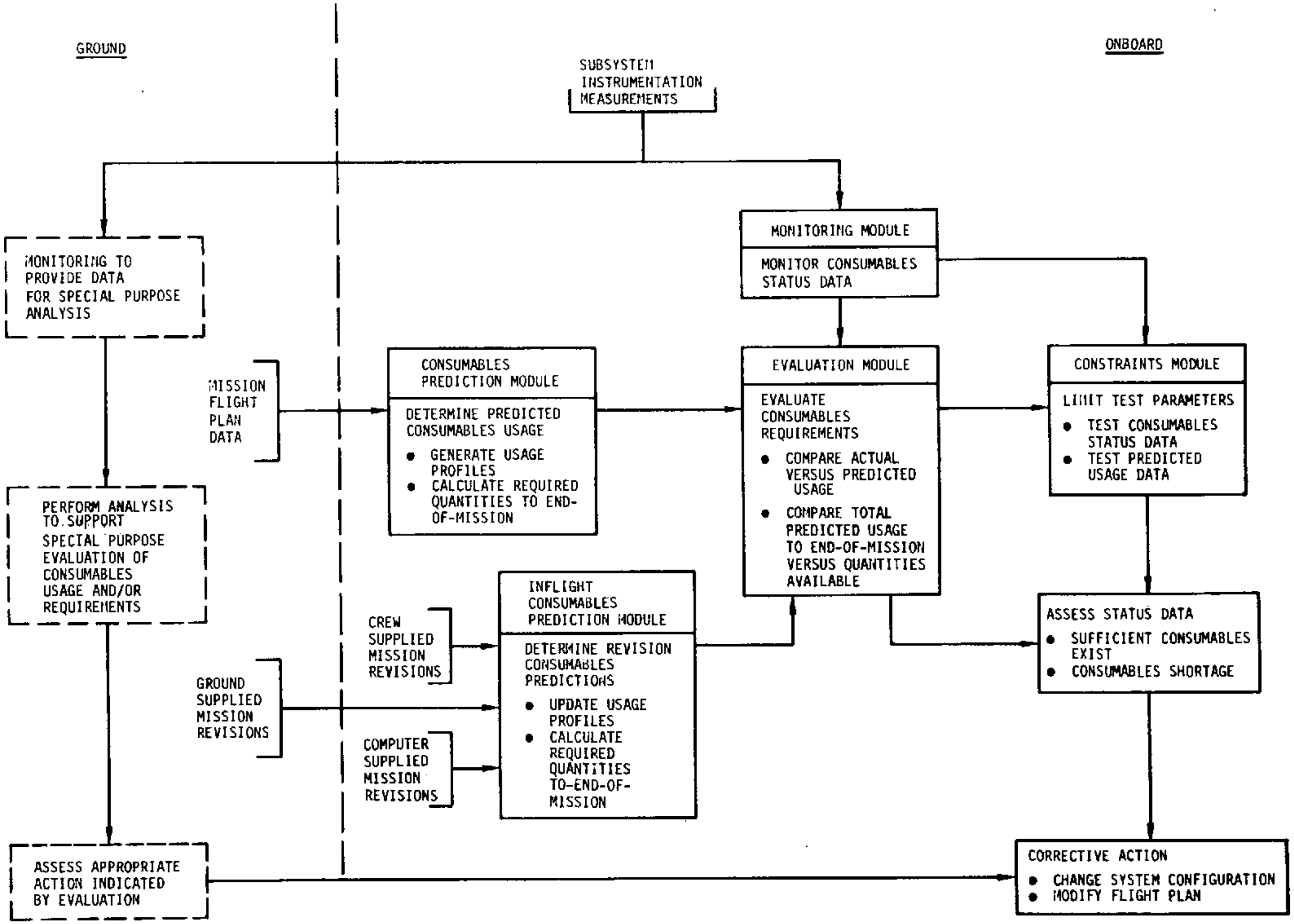


Figure 3-2. Fully Onboard Consumables Management Concept

A result of the ground system checkout operation will be to verify that sufficient consumables have been loaded to support the planned mission. The Monitoring Module is used to calculate the actual consumables quantities onboard the vehicle. The Evaluation and Constraints Modules verify that sufficient end-of-mission reserves are available for each consumable. If the consumables management software detects insufficient quantities of consumables are loaded, an appropriate discrete signal would be issued to the annunciator software. Upon receipt of a consumable violation indication, the annunciator software will display a precoded message on the bottom line of the CRT display to announce the violation. Action would then be required by the ground to correct the detected problem.

3.2.2 Inflight Consumables Management System Operation

The three basic modes of operation associated with inflight consumables management are 1) monitoring and evaluation of consumables status data, 2) inflight contingency replanning of consumables usage based on status data evaluation, and 3) inflight replanning of consumables usage to support payload operations. The mode which performs monitoring and evaluation employs the Monitoring, Evaluation, and Constraints Modules of the consumables management system. In this mode, the three modules are called on a routine, periodic basis by the sequencer in order to determine the consumables status data. If a limit value violation is detected by the consumables management software, a discrete signal is issued to the annunciator software. Each violation discrete signal has a precoded message associated with it to indicate the appropriate CRT display to be selected in obtaining further information regarding the violation. The precoded message may be displayed on the bottom line of the CRT display so as to not interfere with the existing display data. Crew action is required to determine the cause and assess the impact of the consumable violation.

Basically the violations will fall into one of two categories. First, an immediate action problem, such as a storage tank leak, will require immediate crew attention. Second, a predicted violation, such as a predicted end-of-mission reserve violation, will require crew action to avert an actual violation later in the mission. The second class of violations may require additional use of the consumables management system to replan activities.

Inflight replanning of consumables usage may be used to provide greater mission flexibility and less dependence on real-time ground support. The Consumables Prediction Module is an integral part of the inflight contingency planning activities. The crew may evaluate proposed contingency revisions to the mission operating plan by providing direct manual inputs or auxiliary software inputs to consumables management software. The revised plan is used by the Consumable Prediction Module to evaluate the revised consumables requirements. The Evaluation and Constraints Modules are used to assess the impact of revised consumables requirements as compared to quantities available to insure that adequate consumables are available to support the proposed mission operating plan. When the revised plan has been accepted by the crew, the consumables management software profiles and constraints are automatically revised as required and all future consumables evaluations are based on the revised data.

The inflight consumables replanning software may also be used by the crew to evaluate proposed mission operations changes required to support Shuttle payload operations. Pursual of targets of opportunity which become available during the mission may be evaluated as to the predicted impact on consumables usage by use of the consumables management software. This capability for inflight consumable requirements prediction materially enhances the Shuttle flexibility in supporting payload operation.

3.2.3 Postflight Operations

There are no direct postflight operations associated with the consumables management system. However, in order to provide flight data for improving the consumables management software models, it is necessary to provide postflight analysis of flight data by the ground support system. Flight recorder data or telemetry data acquired during the mission should be utilized by the ground mission planning system to update the consumables prediction software models and to revise the mission class and vehicle particular data for future Shuttle missions. This postflight analysis effort will serve to continually improve the ability of both the ground and onboard systems to predict consumables usage for Shuttle missions.

4. SUBSYSTEM CONSUMABLES MANAGEMENT DESCRIPTIONS

Candidate subsystems were identified for inclusion in the Shuttle consumables management system by evaluating each subsystem which employs expendables as to its capability to be managed or controlled. There are subsystems whose consumables are not readily controllable, such as the Solid Rocket Motor propellant, and therefore, cannot be considered for consumables management. Other subsystems were identified which have very limited controllability of consumables usage and which do not merit elaborate management techniques. Several subsystems are used in such a manner that their consumables usage is readily manageable, and mechanization of techniques to assist the crew in the consumables management process for these subsystems can be accomplished without imposing unrealistic requirements in terms of software or hardware.

There are numerous methods by which the subsystems consumables management concepts can be implemented. In order to demonstrate feasibility of the proposed concepts, as a part of this study an implementation technique was developed for the onboard software which could be applied to management of consumables of each Shuttle subsystem. Techniques which offer either more or less sophistication could have been used to accomplish the consumables management functions, but the technical discussion of the technique for implementing the subsystems consumables management software identifies problems which are common to other techniques which might have been selected.

Software Flow Charts

Functional software flow diagrams are presented which identify one method by which the onboard software may be employed to perform portions of the consumables management functions for each subsystem. Estimates were prepared which show the magnitude of the software storage required for the software described in the flow charts. The techniques used to arrive at the software sizing estimates are discussed in Appendix D.

Subsystems Instrumentation

Instrumentation available to support the consumables management functions was investigated to the extent necessary to ensure that reasonable sensor data requirements were assumed for the implementation techniques presented. A discussion of quantity gauging techniques is presented in Appendix A.

Crew Displays

The man/machine interface is very important to successful operation of the consumables management system because the crew is an essential element in the consumables management process. Suggested forms of some displays are presented in the subsystems discussions. Some additional discussion of displays and their utilization are presented in Appendices B and C.

4.1 AUXILIARY POWER UNITS (APU)

The function of the Auxiliary Power Units is to provide power to drive the hydraulic system during the ascent and entry/landing phases of mission operations. The hydraulic system provides power for thrust vector control of the main engines during ascent and for control of aerodynamic control surfaces during the entry/landing phase. The APU's are not normally operated during the orbital mission phase, and therefore, no active consumables management is required for orbital operations. Consequently, the consumables management system functions are to provide prelaunch verification that adequate consumables are available to support the planned mission and to monitor tank quantities for leakage during orbital operations in order to assure that adequate consumables are available for entry/landing operations.

4.1.1 APU Consumables Management Functions

The consumables required for APU operation are hydrazine fuel and cooling water. Hydrazine is decomposed in a thermal bed into hydrogen, ammonia, and nitrogen gases which are used to drive a turbine. The turbine is coupled to a gearbox which drives hydraulic pumps in generating the required hydraulic power. Cooling water is evaporated to provide cooling for the gearbox lubricating oil and hydraulic fluid.

The functions proposed for APU onboard consumables management include verifying that adequate consumable quantities are available for the mission and monitoring consumables status to verify that adequate reserves are maintained during the mission. Both consumable quantities and usage rates are monitored and checked for violations of limit values which are defined by the ground support system prior to the mission.

4.1.2 APU Concept Selection Considerations

The primary factor in selecting an APU consumables management concept is the fact that relatively little inflight control can be exercised to control consumables usage. For defined ascent and entry/landing profiles, the APU consumables requirements are quite predictable by premission analysis. Since APU operation is mandatory for these mission phases and there are no effective means of regulating consumables usage during APU operational periods, the role of a consumables management system is reduced to 1) a primary function of monitoring consumables quantities for leak detection during orbital operations to assure that adequate quantities are available to complete entry/landing operations, and 2) a secondary function of prelaunch verification that adequate consumbales quantities are available to support the planned mission.

4.1.3 APU Onboard Software Description

The APU consumables management software provides for monitoring consumables status and testing parameters for constraint violations. The software can be utilized for monitoring and constraints checking during both prelaunch and inflight operations. All premission planning, consumables usage profile generation, evaluation, replanning, and postflight analysis is accomplished by the ground support system. The onboard software operation is described for both the prelaunch and inflight activities; the same onboard software is utilized for both activities.

Prelaunch Monitoring and Constraints Tests

The functional software flow for the prelaunch operations is shown in Figure 4.1-1. The onboard software sequence of operation is initiated by the ground support system which supplies the preflight planning data to the software. Data required are hydrazine and cooling water loading quantities, consumables usage profiles for each APU, and parameter limit values for constraints tests. Constraints data will include the redline values for each APU consumable and the allowable usage rate versus time. During orbital operations, the usage rate constraint is equivalent to a maximum allowable leakage rate.

After the ground supplied data is loaded and processed, the onboard software performs the monitoring and constraints testing functions. Loaded consumables quantities are compared with the ground supplied values for consumables quantities required in order to verify that adequate hydrazine and cooling water supplies are provided. Inadequate consumables quantities will be detected by the constraints tests and a constraint violation will be provided to warn the ground that a problem exists. Consumables quantity changes are the basis for software calculations of usage rates; detection of a usage rate prior to APU activation will indicate that leakage is occurring and appropriate ground support action is required.

Inflight Monitoring and Constraints Tests

The functional software flow for inflight APU consumables management is shown in Figure 4.1-2. Actual quantities of hydrazine and cooling water are monitored and, from quantity changes, usage rates are calculated in the Monitoring Module. Usage rates are extrapolated to ascertain the mission time at which redline violations are predicted to occur. Quantity, usage rate, and time-to-break redline values are tested in the Constraints Module for violation of limit values. During orbital operations, a constraint violation indicates that a consumable leakage problem exists; subsequent action will be determined by the crew and/or ground support analysis of the problem.

4.1.4 Input/Output Data Description

4.1.4.1 Mission Description Data

A. Input Data Required

The APU consumables management data which follow are required for entry in the onboard software prior to launch.

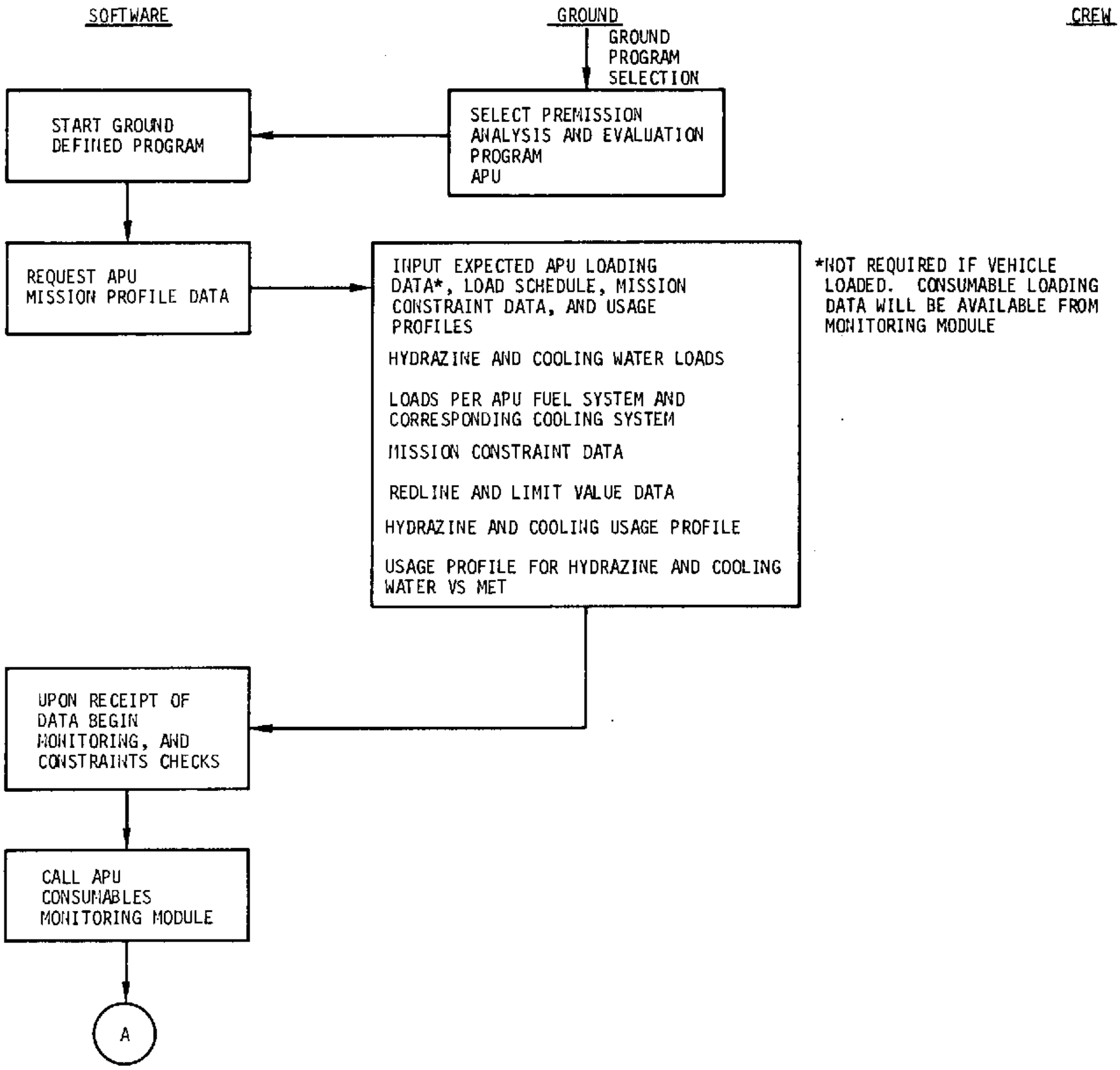


Figure 4.1-1. APU Prelaunch Monitoring and Constraints Test Sequence

SOFTWARE | GROUND | CREW

A

APU CONSUMABLES MONITORING MODULE

CALCULATE THE HYDRAZINE AND WATER USAGE RATES AND TIME TO BREAK REDLINE.

OBTAIN DATA FROM DATA BASE

INPUT

- HYDRAZINE QUANTITY/TANK FOR T_{NOW}
- COOLING WATER QUANTITY/TANK FOR T_{NOW} AND $T_{PREVIOUS}$

DETERMINE USAGE RATES

$$\dot{m}_{N_2H_4} \text{ TANK (I)} = \left[\text{QUAN.}_{N_2H_4} \text{ TANK (I)}_{T_{PREVIOUS}} - \text{QUAN.}_{N_2H_4} \text{ TANK (I)}_{T_{NOW}}\right] \Big/ (T_{NOW} - T_{PREVIOUS})$$

$$\dot{m}_{H_2O} \text{ TANK (I)} = \left[\text{QUAN. } H_2O \text{ TANK (I)}_{T_{PREVIOUS}} - \text{QUAN. } H_2O \text{ TANK (I)}_{T_{NOW}}\right] \Big/ (T_{NOW} - T_{PREVIOUS})$$

I = 1,4

CALCULATE TIME TO BREAK REDLINES (TTBR)

$$N_2H_4 \text{ TANK (I) TTBR} = \left[\text{QUAN } N_2H_4 \text{ TK (I) @ } T_{NOW} - \text{REDLINE QUAN. TK (I)}\right] \Big/ \dot{m}_{N_2H_4} \text{ TANK (I)}$$

$$H_2O \text{ TANK (I) TTBR} = \left[\text{QUAN } H_2O \text{ TK (I) @ } T_{NOW} - \text{REDLINE QUAN. TK (I)}\right] \Big/ \dot{m}_{H_2O} \text{ TANK (I)}$$

I = 1,4

STORE OUTPUT IN DATA BASE

OUTPUT

- N_2H_4 USAGE RATE PER TANK
- H_2O USAGE RATE PER TANK
- TTBR PER N_2H_2 TANK
- TTBR PER H_2O TANK
- N_2H_4 QUANTITY PER TANK
- H_2O QUANTITY PER TANK

CALL APU CONSUMABLES CONSTRAINTS MODULE

APU CONSUMABLES CONSTRAINTS MODULE

PERFORM LIMIT CHECKS AND SET FLAGS AS REQUIRED

OBTAIN INPUT FROM DATA BASE

- N_2H_4 USAGE/TANK
- H_2O USAGE/TANK
- TTBR PER N_2H_4 TANK
- TTBR PER H_2O TANK
- N_2H_4 QUANTITY TANK (I) @ T_{NOW}
  I = 1,4
- H_2O QUANTITY TANK (I) @ T_{NOW}
  I = 1,4
- N_2H_4 REQUIRED VS MISSION TIME PER APU
- H_2O REQUIRED VS MISSION TIME PER APU

Figure 4.1-1. APU Prelaunch Monitoring and Constraints Test Sequence (Continued)

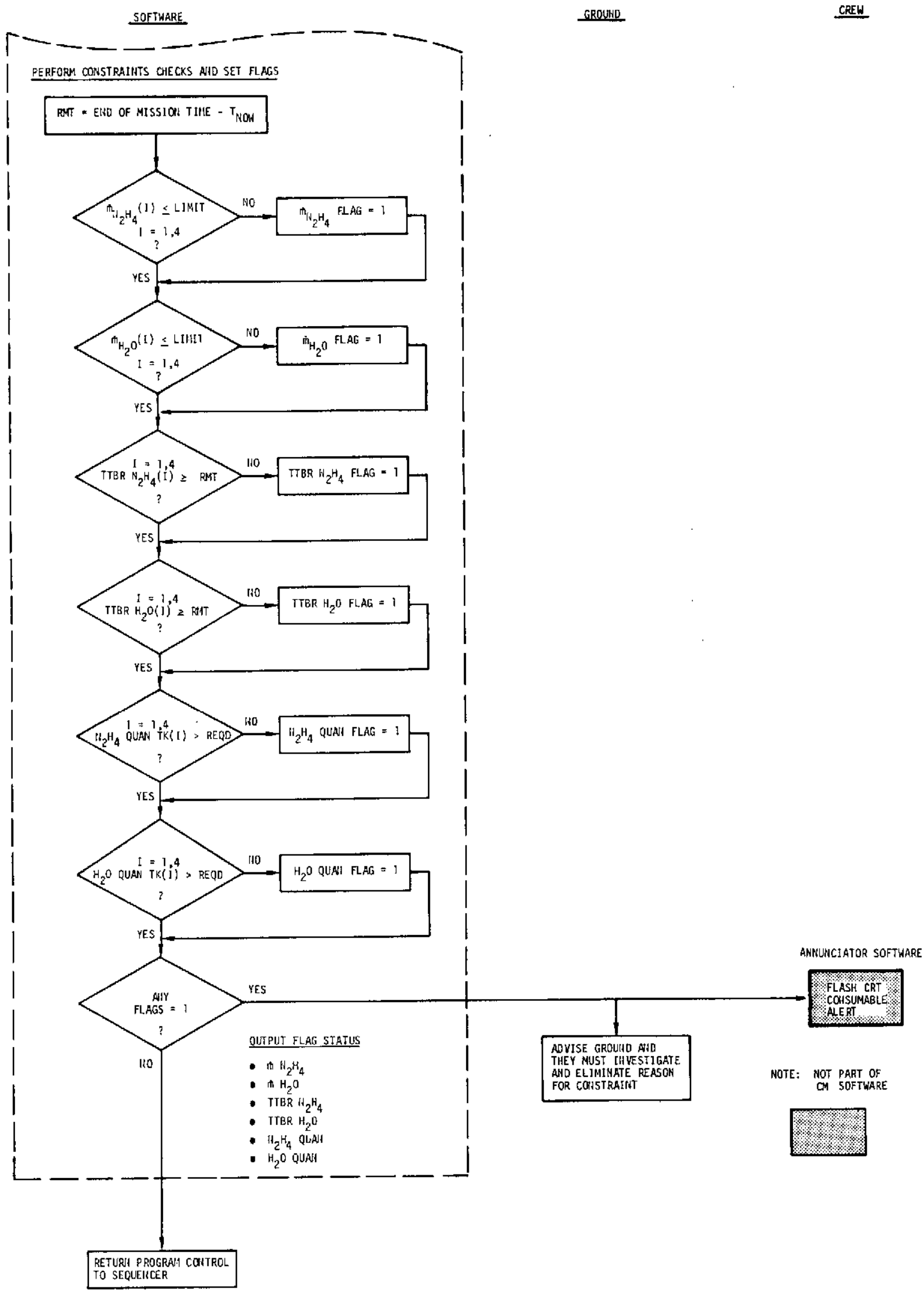


Figure 4.1-1. APU Prelaunch Monitoring and Constraints Test Sequence (Concluded)

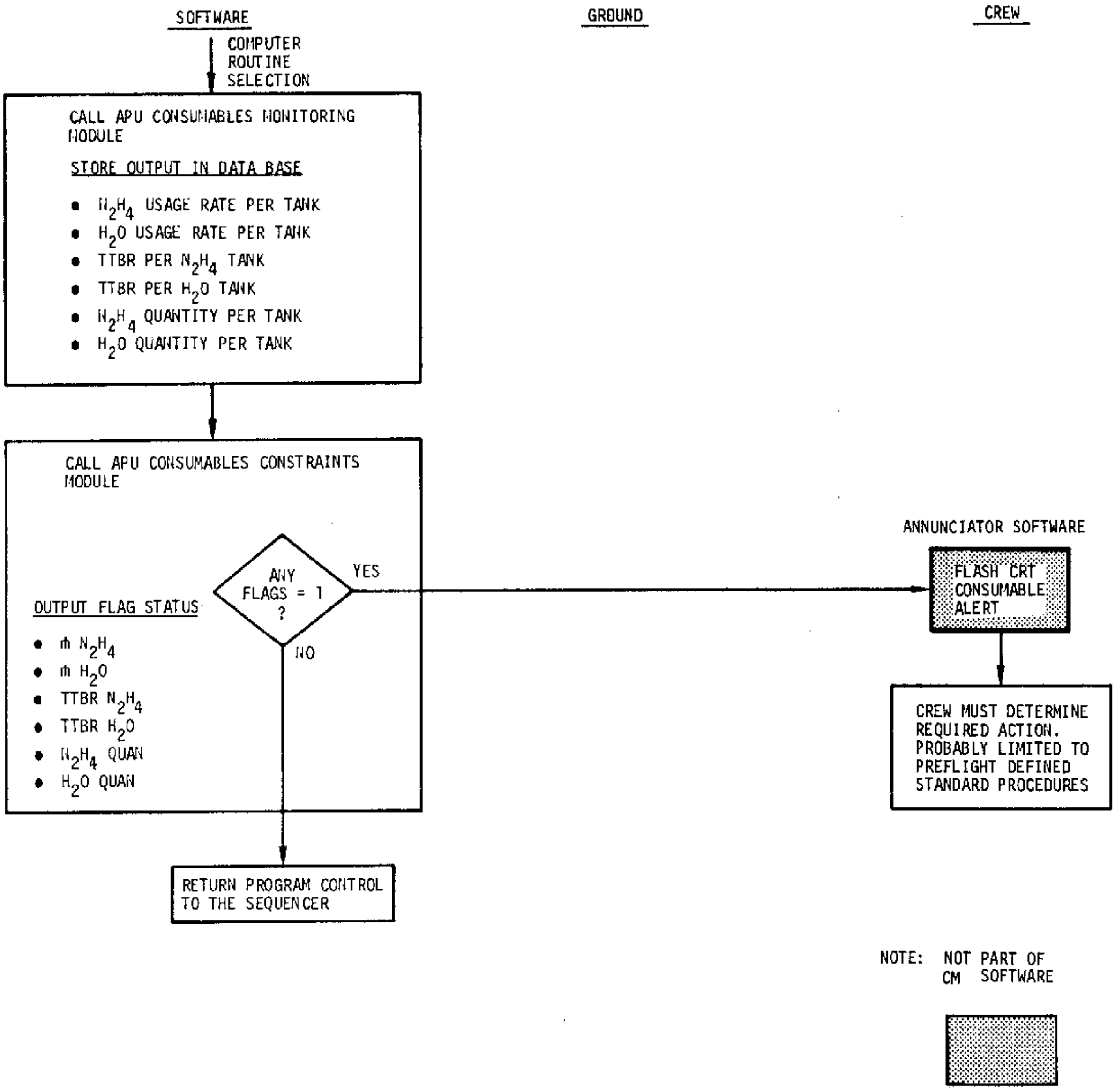


Figure 4.1-2. APU Inflight Monitoring and Constraints Test Sequence

Consumables Loading Requirements - The required quantities of hydrazine and cooling water for each APU shall be supplied.

Constraints Data - Limit values shall be supplied for usage rates of hydrazine and cooling water as functions of mission elapsed time. Redline values for hydrazine and cooling water quantities shall be required for each APU.

Consumables Usage Profiles - Profiles of total hydrazine and cooling water requirements versus mission elapsed time shall be provided.

B. Form of Input Data

The typical forms of input data are listed below.

Consumables Loading Requirements -

APU	N_2H_4 (lbs)	H_2O (lbs)
1	XX	XX
2	XX	XX
3	XX	XX
4	XX	XX

Constraints Data -

	Usage Rate Limits			
MET	APU1	APU2	APU3	APU4
T_1	XX	XX	XX	XX
T_2	XX	XX	XX	XX
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
T_{EOM}	XX	XX	XX	XX

Redline Values

APU	N_2H_4 (lbs)	H_2O (lbs)
1	XX	XX
2	XX	XX
3	XX	XX
4	XX	XX

Consumables Usage Profiles -

MET	N_2H_4 (lbs)	H_2O (lbs)
T_1	XX	XX
T_2	XX	XX
.	.	.
.	.	.
.	.	.
T_{EOM}	XX	XX

4.1.4.2 APU Consumables Monitoring Data

A. Parameters Required

The parameters which are required as inputs to the onboard software for performing consumables management functions include 1) hydrazine quantity for each APU, and 2) cooling water quantity for each APU.

B. Measurement Technique

Hydrazine Quantity

A number of measurement methods are available to provide hydrazine quantity indications which would be acceptable for consumables management purposes. Capacitance probe measurements are sufficiently accurate except under zero-gravity conditions. Since a primary purpose of the APU consumables management system is to provide quantity gauging during orbital operations, capacitance probe measurements would not satisfy the zero-gravity monitoring requirement.

Pressure-Volume-Temperature (PVT) gauging provides measurements for calculating quantity under gravity or zero-g conditions, and therefore, is adequate for APU hydrazine quantity measurement.

The gas density, or ρV, gauging technique provides good accuracy and is operable under zero-g environments. The increased accuracy of this technique over PVT gauging makes it most attractive for measuring APU hydrazine quantities.

Water Quantity

At the present time, information is not available concerning the cooling water storage system design, and therefore, no specific gauging techniques were investigated for this application. The guaging technique should provide water quantity measurements of sufficient accuracy to detect leakage during orbital operation under zero-g conditions and to assure that adequate cooling water is available to support APU operation during the entry/landing phase.

4.1.4.3 Crew Displays and Controls

A. Display Data

Two types of display data should be available for APU consumables management. First, any constraint violation detected by the consumables management software will produce a crew alert signal which shall result in a warning being displayed to the crew. The warning should be accompanied by an indication of the display to be selected for obtaining further information about the nature of the constraint violation.

Second, a display of quantity and usage rates of APU hydrazine and cooling water should be available for selection at crew option.

B. Display Type

A typical CRT tabular data display such as that presented below would provide the required APU consumables information.

	Fuel		Cooling Water	
APU	Quantity	Usage Rate	Quantity	Usage Rate
1	XX	XX	XX	XX
2	XX	XX	XX	XX
3	XX	XX	XX	XX
4	XX	XX	XX	XX

4.1.5 APU Consumables Management Software Estimates

Sizing estimates were prepared for the APU consumables management software described in the flow charts presented in Figures 4.1-1 and 4.1-2.

The estimates are summarized in Table 4.1-1 which shows both dynamic and fixed data storage estimates for each functional module.

A. Dynamic Data Storage Estimates

Dynamic data is defined as the total of the ground supplied prelaunch data and the actual, or historical, data acquired during flight. The maximum dynamic data storage estimate was obtained by preparing estimates of ground input data and total flight data required to perform the APU consumables management functions.

The flight data of interest are APU hydrazine and cooling water quantities and usage rates. The usage rates are calculated by using the quantity change indicated by the two most recent quantity measurements. There is no necessity for storing additional flight data since no long term trend analysis is required. Thus, two quantity values and one usage rate value of each consumable for each APU system satisfy the flight data requirements.

Estimates of ground supplied data storage requirements were obtained by assuming both the number of entries required and the size of each entry. Thirteen events were assumed for the maximum number of entries with data contained in each entry for describing events, total consumables remaining requirements, consumables constraints, and loading schedules.

B. Fixed Data Storage Estimates

Fixed data storage estimates were prepared by estimating the software required for performing the operations in the APU consumables algorithms. Temporary storage of variables and instruction storage are included in the requirements shown.

Table 4.1-1 APU Consumables Management Software Sizing Estimates

MODULE	FIXED STORAGE (words)	DYNAMIC STORAGE (words)
Prediction	10	360
Monitoring	70	20
Constraints	95	5

4.2 ENVIRONMENTAL CONTROL AND LIFE SUPPORT SUBSYSTEM (ECLSS)

The ECLSS performs atmospheric revitalization, life support, and thermal control functions in support of crew and orbiter equipment operation during all mission phases. The mandatory functions performed by the ECLSS results in a high priority being placed on management of ECLSS consumables throughout the mission in order to assure that capability is provided to support nominal and contingency operations. Atmospheric revitalization provides an oxygen/nitrogen cabin atmosphere at 14.7 psia with control of carbon dioxide partial pressure, humidity, and temperature to furnish a shirt-sleeve crew environment. The life support system provides for food and waste management control and for extravehicular/intravehicular activities. Thermal control is provided for avionics and mechanical equipment and for the crew compartment. In addition, potable water management is provided to assure that adequate water is available at all times and that excess water disposal can be completed without interference with scheduled mission activities.

The ECLSS consumables management functions and techniques are different for the various consumables. Therefore, each consumable and its support functions were studied individually to select the recommended consumables management concept.

4.2.1 ECLSS Consumables Management Functions

The ECLSS consumables required for Shuttle operation include oxygen, nitrogen, lithium hydroxide, ammonia, water, and biocide.

Oxygen

The ECLSS oxygen primary supply source is the cryogenic storage system; additional oxygen is stored in gaseous form in a high pressure tank. ECLSS oxygen is consumed by 1) metabolic consumption, 2) pressurization and external leakage, and 3) waste management purges. ECLSS oxygen consumables management functions include monitoring the oxygen usage rate and evaluating the total oxygen required to complete the mission as scheduled.

Nitrogen

Nitrogen is stored as a gas and is used to pressurize the crew compartment. Nitrogen users include pressurization and external leakage and waste management purges. The consumables management functions for nitrogen are to monitor the quantity available and to evaluate the capability to support the mission as scheduled.

Lithium Hydroxide

Lithium hydroxide is contained in cannisters through which the cabin air is circulated to remove carbon dioxide generated by the crew. Two cannisters are installed in the system for simultaneous operation and an alternate cannister is replaced every twelve hours. The consumables management function is to monitor the cannister change cycle to assure that an adequate number of cannisters are available to support the scheduled mission.

Ammonia

Ammonia is stored as a liquid and is used to provide cooling during atmospheric flight for the entry/landing mission phase. Ammonia is boiled to dissipate heat during entry when the space radiator is not operated and therefore, any usage prior to entry must be due to leakage. The consumables management function is to monitor the ammonia quantity and, in the event of leakage, to evaluate the impact of leakage on the entry schedule.

Water

Water presents a unique consumable management problem in that it is both consumed and produced onboard. Water is produced, as a by-product of fuel cell operation, in sufficient quantities as to make disposal of excess water necessary. Management of water will probably be accomplished by scheduling periods of water sublimation or dumps as required to maintain potable water tank quantities within specified upper and lower limits. The consumables management function is to monitor water tank quantities and to provide data for scheduling water disposal without interferring with the mission activities.

Biocide

The biocide consumable is stored as a liquid and is used as a disinfectant in the urine disposal system. The subsystem design has not progressed to the point that the consumables management function can be firmly defined. However, it is anticipated that the consumables management requirements can be satisfied with the capability to monitor quantity and predict the end-of-mission reserves.

4.2.2 ECLSS Concept Selection Considerations

The management technique for each ECLSS consumable was selected according to the individual consumable requirements for management, but, in general, the major factor influencing concept selections was the fact that there is limited flexibility for controlling ECLSS consumables usage. The ECLSS performs a supportive role for the crew and avionics equipment by providing consumables to support the life functions of the crew and to support thermal control of the cabin atmosphere and avionics equipment. This supportive role makes it essential that ECLSS consumables are provided at all times throughout the mission, and therefore, the consumables usage rates are usually well defined for a nominal mission. The limited flexibility in control of ECLSS consumables usage implies that sophisticated methods are not required to provide the necessary capability for onboard consumables management. Functions essential to the management of each consumable are provided by simplified software which performs monitoring, evaluation, constraints testing, and prediction functions as required.

4.2.3 ECLSS Onboard Software Description

The ECLSS consumables management software provides for monitoring, evaluating, and replanning ECLSS consumables usage. Mission planning and analysis data supplied by the ground support system includes an ECLSS consumable event timeline, consumables usage profiles, and parameter limit values. The onboard consumables management software processes this data and verifies that sufficient consumables are loaded to support the planned mission. Inflight consumables management provides for monitoring and evaluating consumables usage as well as for replanning usage in accordance with mission revisions. Since the consumables management technique varies for each consumable, a brief summary is presented to describe the management approach for each consumable.

Oxygen

The oxygen usage rate is monitored to verify that actual usage is within specified limits, and the average usage rate is used as a basis for predicting oxygen requirements for the remainder of the mission. Control of ECLSS oxygen usage is restricted to controlling the number of pressurizations, controlling metabolic use by regulating the crew activity, and controlling use of the waste management system.

Nitrogen

Monitored parameters include nitrogen quantity remaining and usage rate. Quantity and usage rate values are used in calculating predicted end-of-mission reserves and predicted time that redlines will be violated. Replanning capability includes calculating nitrogen quantity, end-of-mission reserves, and usage profiles for mission revisions. Methods for controlling nitrogen usage include controlling the number of pressurizations and waste management system operation.

Lithium Hydroxide

Manual crew inputs provide indication of cannister replacement for use in the software calculations of predicted lithium hydroxide end-of-mission reserves and time that a redline will be violated. There is normally no control over lithium hydroxide usage other than limited capability to regulate carbon dioxide generation by controlling crew activity. The cannister usage time may be extended by basing cannister replacement criteria on carbon dioxide partial pressure values, rather than on a fixed usage period.

Ammonia

There are no effective means for controlling ammonia usage since only limited control can be provided by reducing the coolant system heat load during entry. However, since prediction of ammonia usage is based on events similar to other ECLSS consumables, it is recommended that the ammonia quantity and usage rate measurements are used in determining predicted end-of-mission reserves and redline violation time to assist the crew in replanning activities.

Water

Water tank quantity and quantity change rates are used to determine when either upper or lower quantity limits will be reached. Water generation rate is determined by fuel cell output power levels, and water consumption rate is determined by metabolic, hygenic, and supplemental heating requirements. The management problem of scheduling dump or sublimation periods is aided by software calculations of time-to-reach limit values.

Biocide

Quantity and usage rate information is used to calculate predicted end-of-mission reserve values and time at which redline violation will occur. Further details of biocide management will depend on how the subsystem is designed.

Prelaunch Analysis and Evaluation

Functional software flow for the ECLSS consumables management software prelaunch operations is shown in Figure 4.2-1. The ECLSS consumables requirements for a planned mission are provided by the ground support system for storage in the onboard computer system. The input data will include the following:

- ECLSS consumables event timeline
- End-of-mission reserve limit values for nitrogen, ammonia, lithium hydroxide, and biocide
- Usage profiles for nitrogen and ammonia
- Lithium hydroxide cannister replacement rate
- Predicted water dump and sublimation times
- Potable water tank quantity limits
- Total quantity requirements to complete the planned mission including oxygen, nitrogen, ammonia, lithium hydroxide and biocide quantities

After the ground supplied data is provided, the ground can initiate the prelaunch evaluation sequence. The Monitoring Module is called to determine actual loaded consumables values which will be compared with predicted requirements. Monitored data includes the following:

Oxygen

Oxygen average flow rate is determined by averaging flow rate measurements. A minimum time period, to be determined later, must be allowed between the flow rate data samples used in this calculation in order to account for the effects of the two gas control system.

Nitrogen

Nitrogen quantity per tank and the sum of tank quantities are monitored. Nitrogen usage rate is determined by calculating the total quantity rate of change. As with oxygen, use of the two gas control system requires that sufficient time elapse between nitrogen quantity samples in order to accurately calculate usage rate.

Lithium Hydroxide

The number of cannisters loaded is provided as software input data and subsequent cannister data requires a crew input to indicate a cannister has been replaced. Lithium Hydroxide end-of-mission reserve calculations are based on a specified cannister replacement cycle.

Water

Quantities contained in each potable water tank are measured, and usage rates calculated from the rate of quantity changes.

Ammonia

Total ammonia quantity is monitored and usage rates calculated from quantity change rate. Prior to entry, any usage rate will be an indication that leakage is occurring and that corrective action is needed.

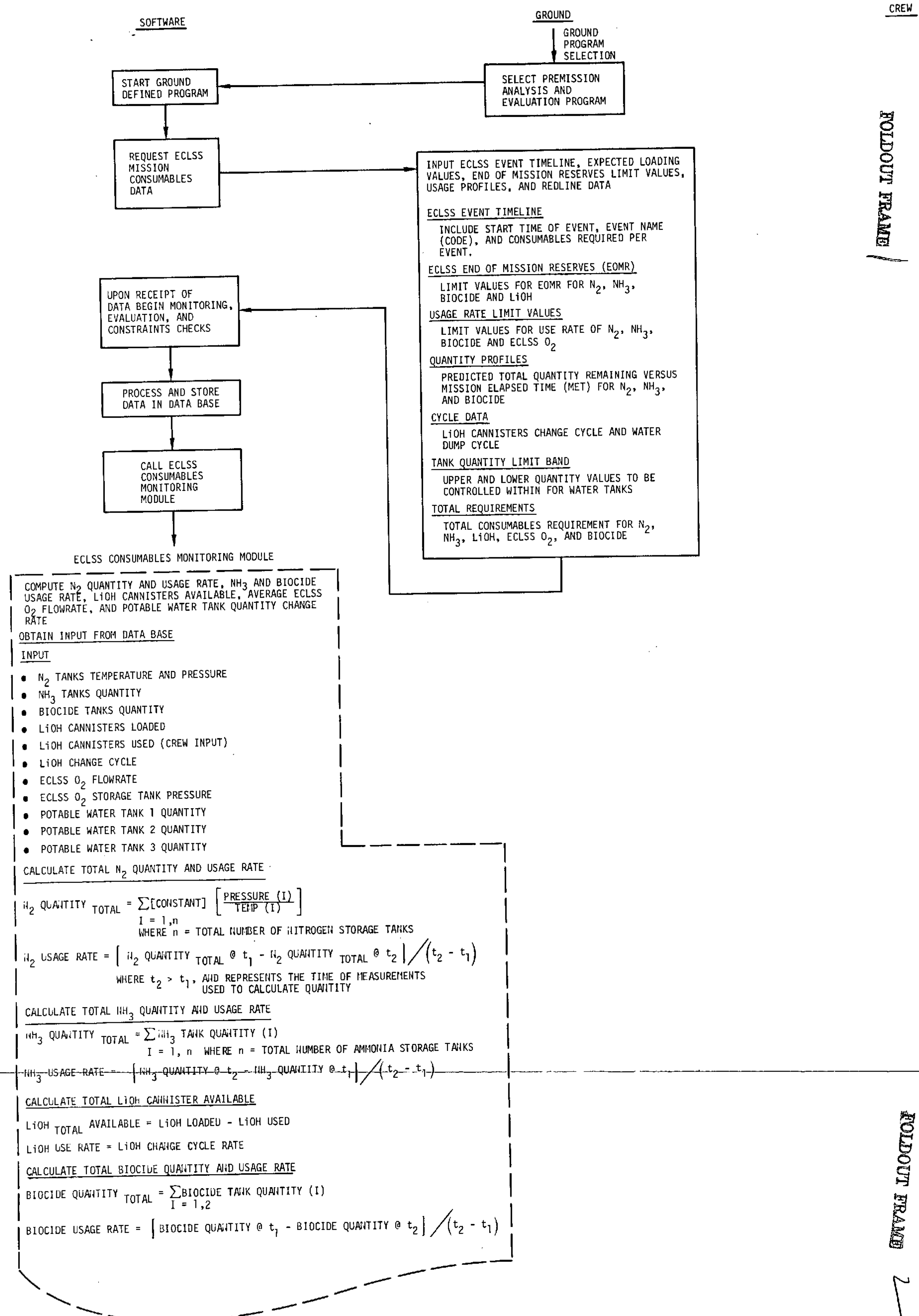


Figure 4.2-1. ECLSS Prelaunch Analysis and Evaluation Sequence.

FOLDOUT FRAME 1
FOLDOUT FRAME 2

SOFTWARE GROUND CREW

CALCULATE ECLSS O_2 FLOW RATE AND STORAGE TANK QUANTITY

ECLSS O_2 FLOW RATE = $\sum$[TDB MEASURED VALUES]*/(TBD MEASUREMENT VALUES)

*THIS IS DETERMINATION OF AVERAGE ECLSS O_2 FLOW RATE. ANY PRESSURIZATIONS OCCURRING DURING THIS TIME MUST BE REMOVED FOR AVERAGING PURPOSES.

ECLSS O_2 STORAGE TK. QUAN$_{TEMP\ =\ CONT.}$= [CONSTANT] [PRESSURE]

CALCULATE QUANTITY CHANGE RATE FOR EACH POTABLE WATER TANK

$\dot{m}(I)^*$ = [H_2O TANK (I) QUANTITY @ t_2 - H_2O TANK (I) @ t_1]/(t_2 - t_1)

I = 1, 3

WHERE $t_2 > t_1$ = TIMES OF H_2O TANK QUANTITY MEASUREMENTS

NOTE: NEGATIVE $\dot{m}$ (I) REPRESENTS TANK DEPLETING AND POSITIVE $\dot{m}$ (I) REPRESENTS TANK FILLING

STORE IN DATA BASE

OUTPUT

- N_2 QUANTITY TOTAL
- N_2 USAGE RATE
- NH_3 QUANTITY TOTAL
- NH_3 USAGE RATE
- TOTAL LiOH CANNISTER AVAILABLE
- LiOH CHANGE CYCLE
- ECLSS O_2 AVERAGE USAGE RATE
- ECLSS O_2 STORAGE TANK QUANTITY
- WATER TANK 1 QUANTITY CHANGE RATE
- WATER TANK 2 QUANTITY CHANGE RATE
- WATER TANK 3 QUANTITY CHANGE RATE
- BIOCIDE QUANTITY TOTAL
- BIOCIDE USAGE RATE

CALL ECLSS CONSUMABLES EVALUATION MODULE

ECLSS CONSUMABLES EVALUATION MODULE

COMPUTE THE END OF MISSION RESERVES, TIME TO BREAK REDLINES, FOR N_2, NH_3, AND LiOH. COMPUTE THE TIME TO FULL OR TIME TO EMPTY THE POTABLE WATER TANKS.

INPUT

- PREDICTED TOTAL N_2 REQUIREMENT TO COMPLETE MISSION FROM T_{NOW}
- N_2 QUANTITY TOTAL @ T_{NOW} (T_{NOW} = PRESENT TIME)
- N_2 REDLINE QUANTITY
- N_2 USAGE RATE
- N_2 QUANTITY PROFILE
- PREDICTED TOTAL NH_3 REQUIREMENT TO COMPLETE MISSION FROM T_{NOW}
- NH_3 QUANTITY TOTAL @ T_{NOW}
- NH_3 REDLINE QUANTITY
- NH_3 USAGE RATE
- NH_3 QUANTITY PROFILE
- PREDICTED LiOH REQUIREMENT TO COMPLETE MISSION FROM T_{NOW}
- TOTAL LiOH CANNISTERS AVAILABLE @ T_{NOW}
- LiOH REDLINE CANNISTER REQUIREMENT
- LiOH CHANGE CYCLE RATE
- LiOH PREDICTED USAGE @ T_{NOW}
- ECLSS O_2 AVERAGE USAGE RATE
- END OF MISSION TIME
- PREDICTED ECLSS O_2 FLOW RATE @ T_{NOW}
- BIOCIDE QUANTITY @ T_{NOW}
- PREDICTED BIOCIDE REQUIREMENT
- BIOCIDE USAGE RATE

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 4.2-1. ECLSS Prelaunch Analysis and Evaluation Sequence (Continued).

SOFTWARE | GROUND | CREW

- H_2O TANK 1 QUANTITY MAXIMUM AND MINIMUM VALUE
- H_2O TANK 2 QUANTITY MAXIMUM AND MINIMUM VALUE
- H_2O TANK 3 QUANTITY MAXIMUM AND MINIMUM VALUE
- H_2O TANKS 1, 2, AND 3 QUANTITY @ T_{NOW} AND $T_{EARLIER}$
- H_2O TANKS 1, 2, AND 3 QUANTITY CHANGE RATES

CALCULATE END OF MISSION RESERVES (EOMR) FOR N_2, NH_3, AND LiOH

N_2 EOMR = [N_2 QUANTITY$_{TOTAL}$ @ T_{NOW} - PREDICTED N_2 REQUIRED TO COMPLETE MISSION FROM T_{NOW}]

BIOCIDE EOMR = [BIOCIDE QUANTITY$_{TOTAL}$ @ T_{NOW} - PREDICTED BIOCIDE REQUIRED TO COMPLETE MISSION FROM T_{NOW}]

NH_3 EOMR = [NH_3 QUANTITY TOTAL @ T_{NOW} - PREDICTED NH_3 REQUIRED TO COMPLETE MISSION FROM T_{NOW}]

LiOH EOMR = [LiOH CANNISTERS AVAILABLE @ T_{NOW} - LiOH PREDICTED REQUIREMENT TO COMPLETE MISSION FROM T_{NOW}]

CALCULATE TOTAL ECLSS O_2 REQUIRED TO COMPLETE MISSION

ECLSS O_2 REQ. = [ACTUAL ECLSS FLOW RATE] [T_{EOM} - T_{NOW}] + [OXYGEN PRESSURIZATION REQUIREMENTS]

CALCULATE TIME-TO-BREAK-REDLINE (TTBR) FOR N_2, NH_3 AND LiOH

N_2 TTBR = [N_2 QUANTITY @ T_{NOW} - REDLINE QUANTITY]/N_2 USAGE RATE

BIOCIDE TTBR = [BIOCIDE QUANTITY @ T_{NOW} - REDLINE QUANTITY]/BIOCIDE USAGE RATE

NH_3 TTBR = [NH_3 QUANTITY @ T_{NOW} - REDLINE QUANTITY]/NH_3 USAGE RATE

LiOH $_{TTBR}$ = [LiOH CANNISTER @ T_{NOW} - REDLINE CANNISTER REQUIREMENT]/ CHANGE CYCLE FOR LiOH

CALCULATE DELTAS BETWEEN ACTUAL AND PREDICTED VALUES

ΔN_2 = [ACTUAL N_2 QUANTITY$_{TOTAL}$ - PREDICTED N_2 QUANTITY$_{TOTAL}$] @ T_{NOW}

ΔBIOCIDE=[ACTUAL BIOCIDE QUANTITY$_{TOTAL}$ - PREDICTED BIOCIDE QUANTITY] @ T_{NOW}

ΔNH_3 = [ACTUAL NH_3 QUANTITY$_{TOTAL}$ - PREDICTED NH_3 QUANTITY TOTAL] @ T_{NOW}

ΔLiOH = [ACTUAL LiOH AVAILABLE - PREDICTED LiOH AVAILABLE] @ T_{NOW}

ΔECLSS O_2 FLOW RATE = [ACTUAL ECLSS O_2 FLOW RATE - PREDICTED ECLSS O_2 FLOW RATE] @ T_{NOW}

CALCULATE TIME TO FULL (TTF) AND TIME TO EMPTY* (TTE) FOR POTABLE WATER TANKS

*NOTE: TIME TO EMPTY IN ALL PROBABILITY WILL BE NON-ZERO. THERE WILL PROBABLY BE AN ABORT QUANTITY REQUIRED FOR EACH WATER TANK.

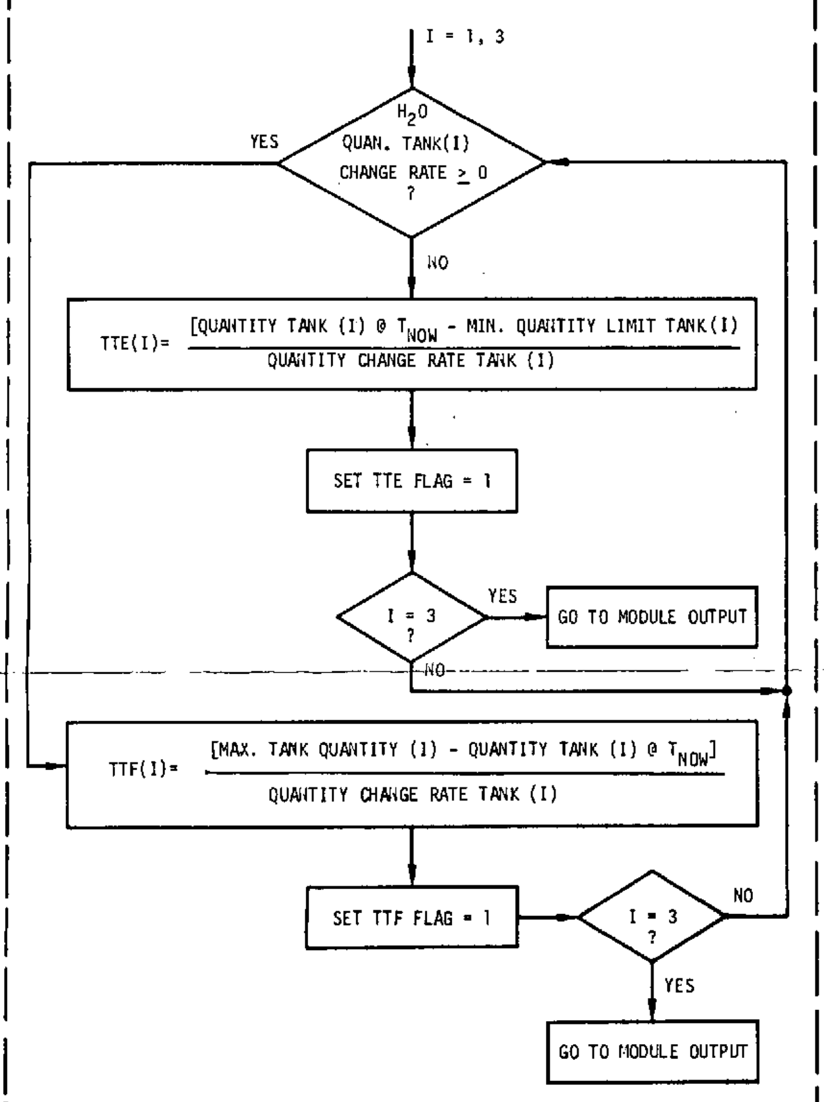
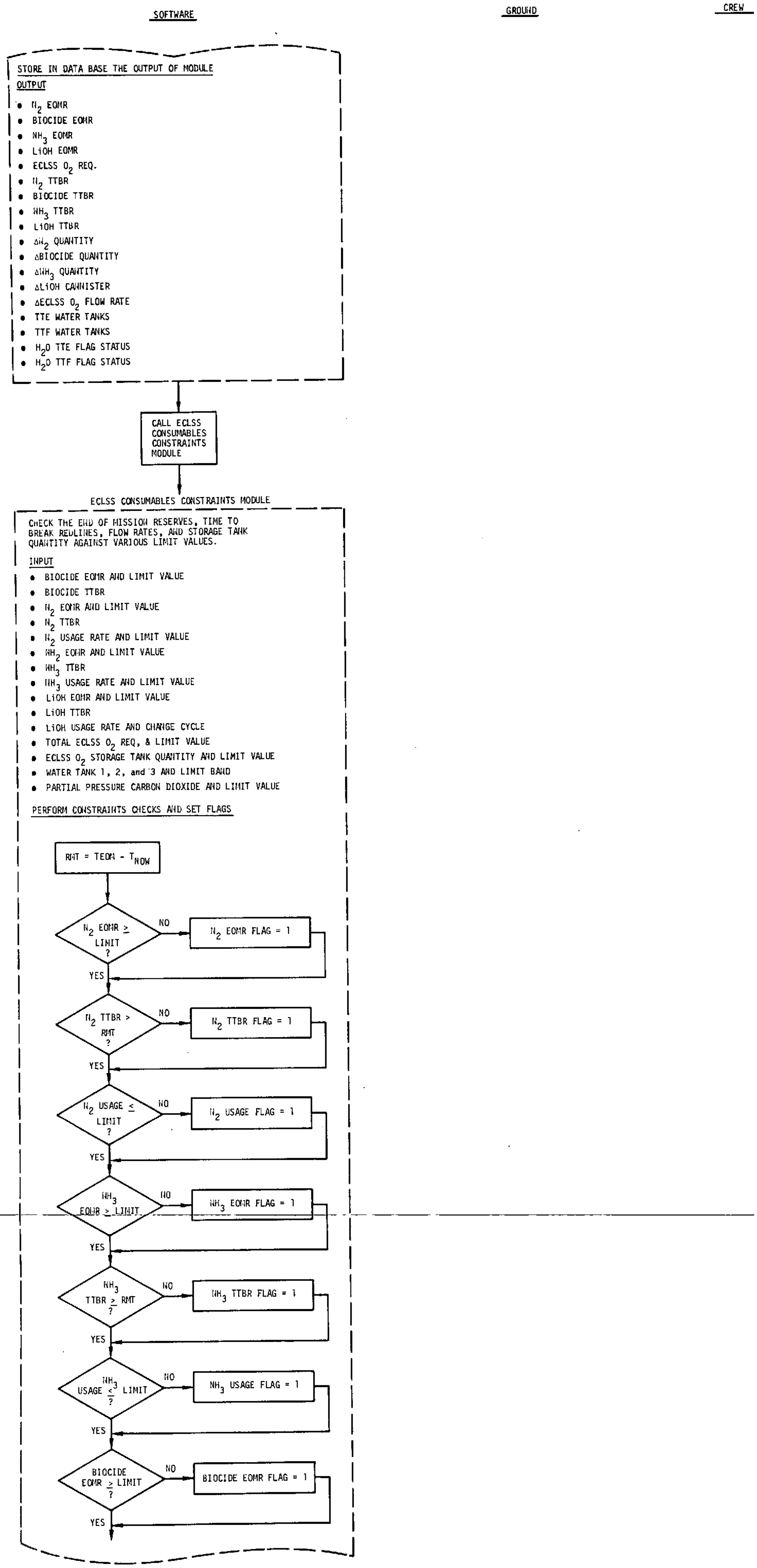


Figure 4.2-1. ECLSS Prelaunch Analysis and Evaluation Sequence (Continued).

FOLDOUT FRAME 1

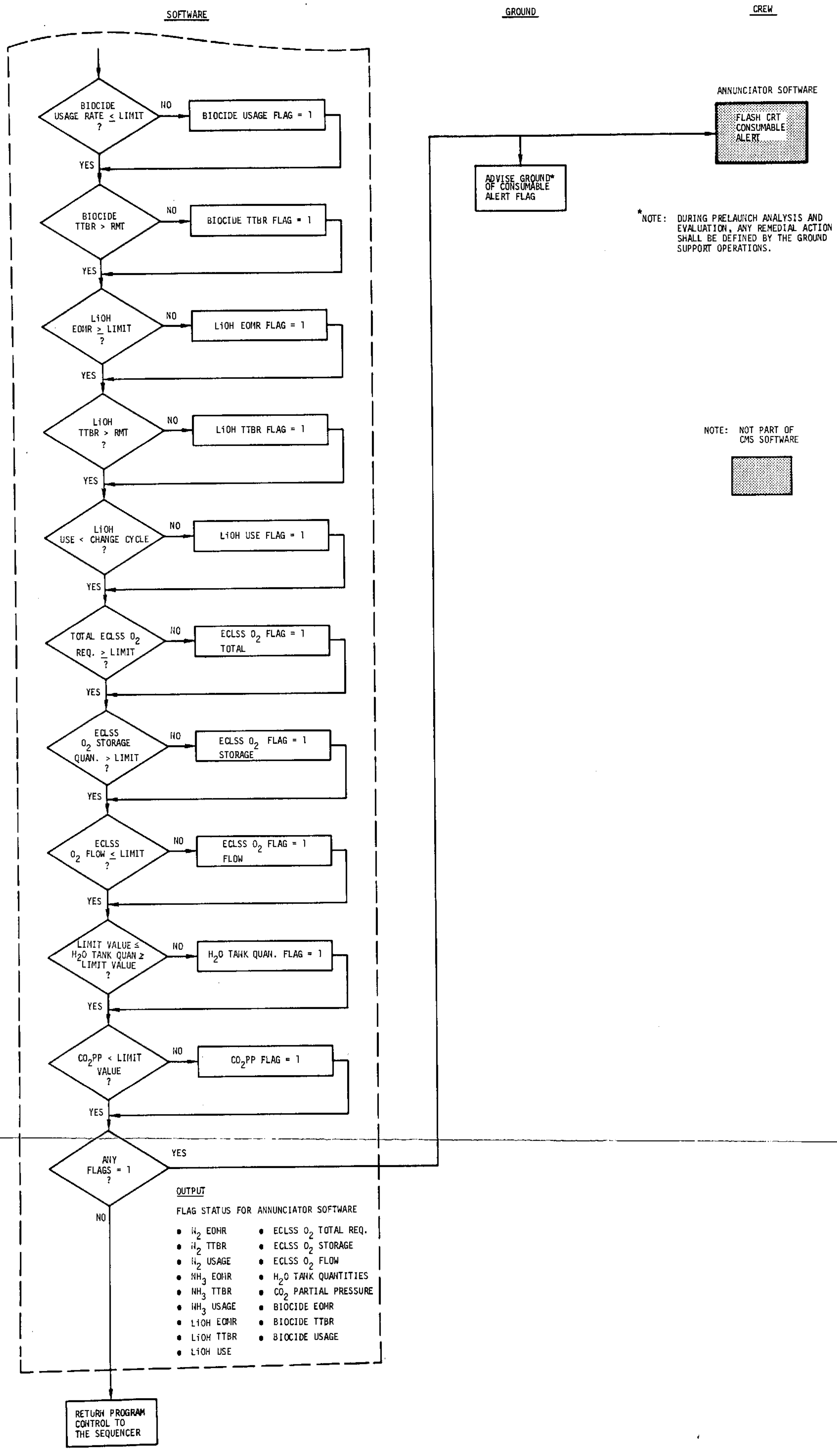
FOLDOUT FRAME 2



FOLDOUT FRAME

FOLDOUT FRAME 2

Figure 4.2-1. ECLSS Prelaunch Analysis and Evaluation Sequence (Continued).



FOLDOUT FRAME

FOLDOUT FRAME 2

Figure 4.2-1. ECLSS Prelaunch Analysis and Evaluation Sequence (Concluded).

After the monitoring sequence is completed, the ECLSS consumables Evaluation Module is called to evaluate the monitored ECLSS data. Computations are performed to determine end-of-mission reserves (EOMR), time to break redlines (TTBR), and total ECLSS consumables required to complete the mission. The ECLSS oxygen requirement is provided to the FCCS consumables management software for use in performing cryogenic oxygen management.

The results of the evaluations are tested in the Constraints Module to determine if computed values for end-of-mission reserves, time to break redlines, and usage rates are within specified limits. Any constraint violations will produce an alert signal to the ground to indicate that corrective action is required.

Inflight Monitoring and Evaluation

The software flow for the ECLSS monitoring and evaluation sequence is shown in Figure 4.2-2. The consumables management software required for this sequence is the same as that used for the prelaunch analysis and evaluation sequence. Periodically during the mission the ECLSS consumables management software will monitor the consumables status, evaluate the actual status data as compared to predicted, and perform limit value tests for constraint violations.

A constraint violation will result in a signal being issued to alert the crew of a problem. The crew may then select an ECLSS consumables data display to aid in assessing the source of the violation and the appropriate action to follow. One possible course of action is to replan portions of the mission in order to reduce consumables usage to acceptable levels.

Inflight Consumables Predictions

There are three major features provided by the ECLSS inflight consumables prediction sequence. As shown in Figure 4.2-3, the update entry, manual entry consumables prediction, and automatic entry consumables prediction are features which may be utilized for ECLSS consumables management.

The update entry may be selected to shift the predicted consumables profiles so that the predicted profile values at T_{NOW} coincide with actual consumables status at T_{NOW}. Selecting the update feature does not involve any revising of the remainder of the mission. Therefore, the shape of the predicted usage profile is unchanged by the update. The update entry mode is useful for situations in which the past mission events have resulted in actual consumables usage deviating from the predicted usage profiles to the extent that it is difficult to properly interpret the displayed information.

Real-time mission revisions which affect predicted ECLSS consumables usage will require that an updated prediction be performed to reflect the planned revisions. Adding, deleting, or rescheduling events such as airlock pressurizations and Extravehicular Life Support System recharges are typical of revisions which would require an updated consumables prediction. Changes of this type will require the crew to provide manual data entries for revising the mission plan information stored in the computer. Prior to revising the stored mission plan, the crew may perform a trial mission revision to determine if the revision is acceptable and that no constraints will be violated; an acceptable trial revision would then be entered to update the stored mission plan.

Automatic ECLSS usage predictions are provided for certain specific types of mission revisions by utilizing data calculated by non-consumables management software. Typical data for automatic entry would include guidance and navigation calculations of revised total mission time. The revised data would then be used for calculating an updated ECLSS consumables prediction.

4.2.4 ECLSS Input/Output Data Description

4.2.4.1 Mission Description Data

A. Input Data Required

The ECLSS consumables management data listed below are required for entry in the onboard software prior to launch.

Consumables Event Timeline

A tabular listing of ECLSS consumables events versus mission elapsed time is required.

SOFTWARE | GROUND | CREW

COMPUTER ROUTINE SELECTION

CALL ECLSS CONSUMABLES MONITORING MODULE

OUTPUT

- N_2 QUANTITY TOTAL
- N_2 USAGE RATE
- NH_3 QUANTITY TOTAL
- NH_3 USAGE RATE
- TOTAL LiOH CANNISTER AVAILABLE
- LiOH CHANGE CYCLE
- ECLSS O_2 AVERAGE USAGE RATE
- ECLSS O_2 STORAGE TANK QUANTITY
- WATER TANK 1 QUANTITY CHANGE RATE
- WATER TANK 2 QUANTITY CHANGE RATE
- WATER TANK 3 QUANTITY CHANGE RATE
- BIOCIDE QUANTITY TOTAL
- BIOCIDE USAGE RATE

CALL ECLSS CONSUMABLES EVALUATION MODULE

OUTPUT

- N_2 EOMR
- NH_3 EOMR
- LiOH EOMR
- ECLSS O_2 REQ.
- N_2 TTBR
- NH_3 TTBR
- LiOH TTBR
- ΔN_2 QUANTITY
- ΔNH_3 QUANTITY
- ΔLiOH CANNISTER
- ΔECLSS O_2 FLOW RATE
- TTE WATER TANKS
- TTF WATER TANKS
- H_2O TTE FLAG STATUS
- H_2O TTF FLAG STATUS
- BIOCIDE EOMR
- BIOCIDE USAGE
- BIOCIDE TTBR

A

FOLDOUT FRAME

FOLDOUT FRAME 2

Figure 4.2-2. ECLSS Inflight Monitoring and Evaluation Sequence.

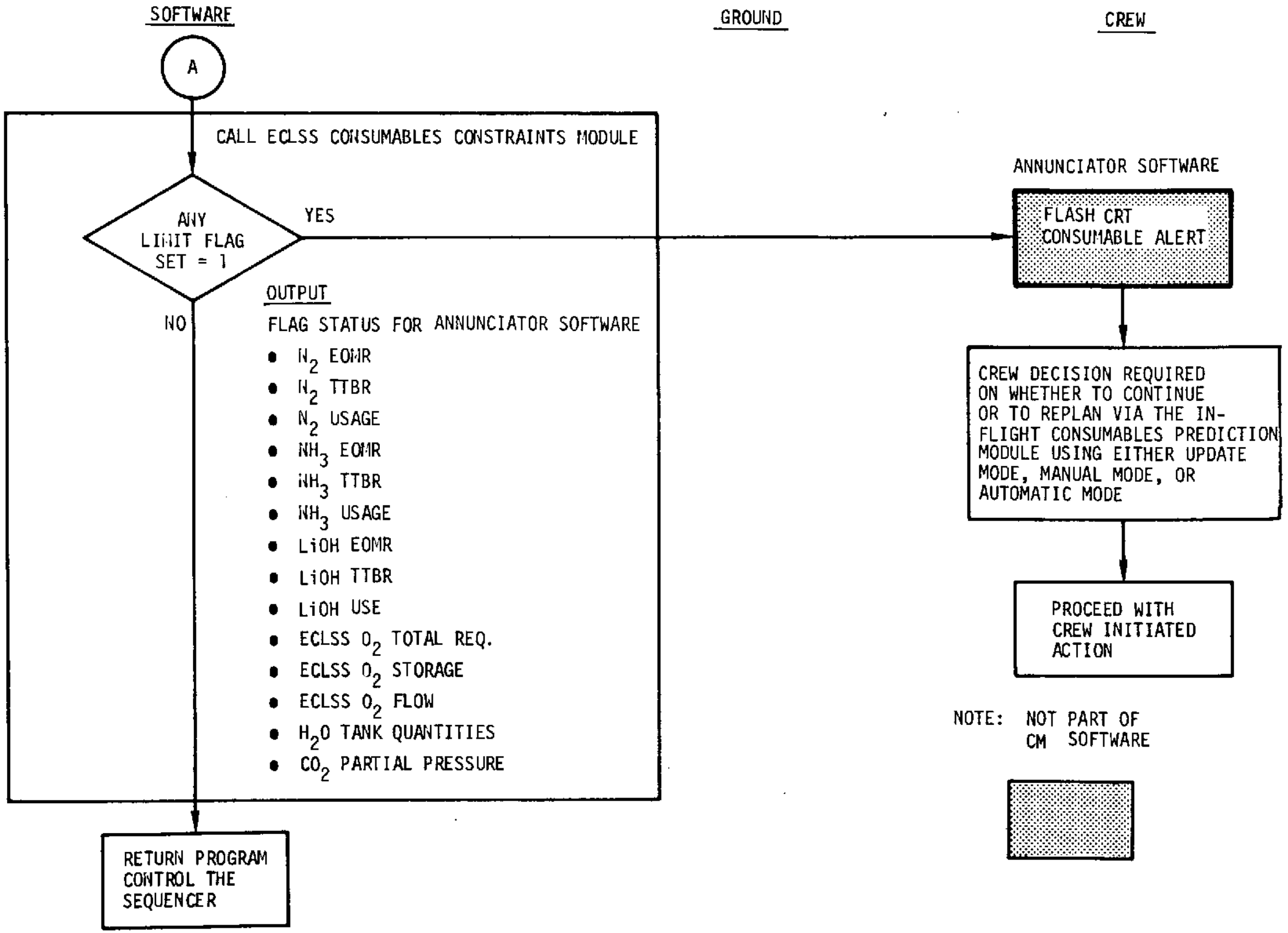
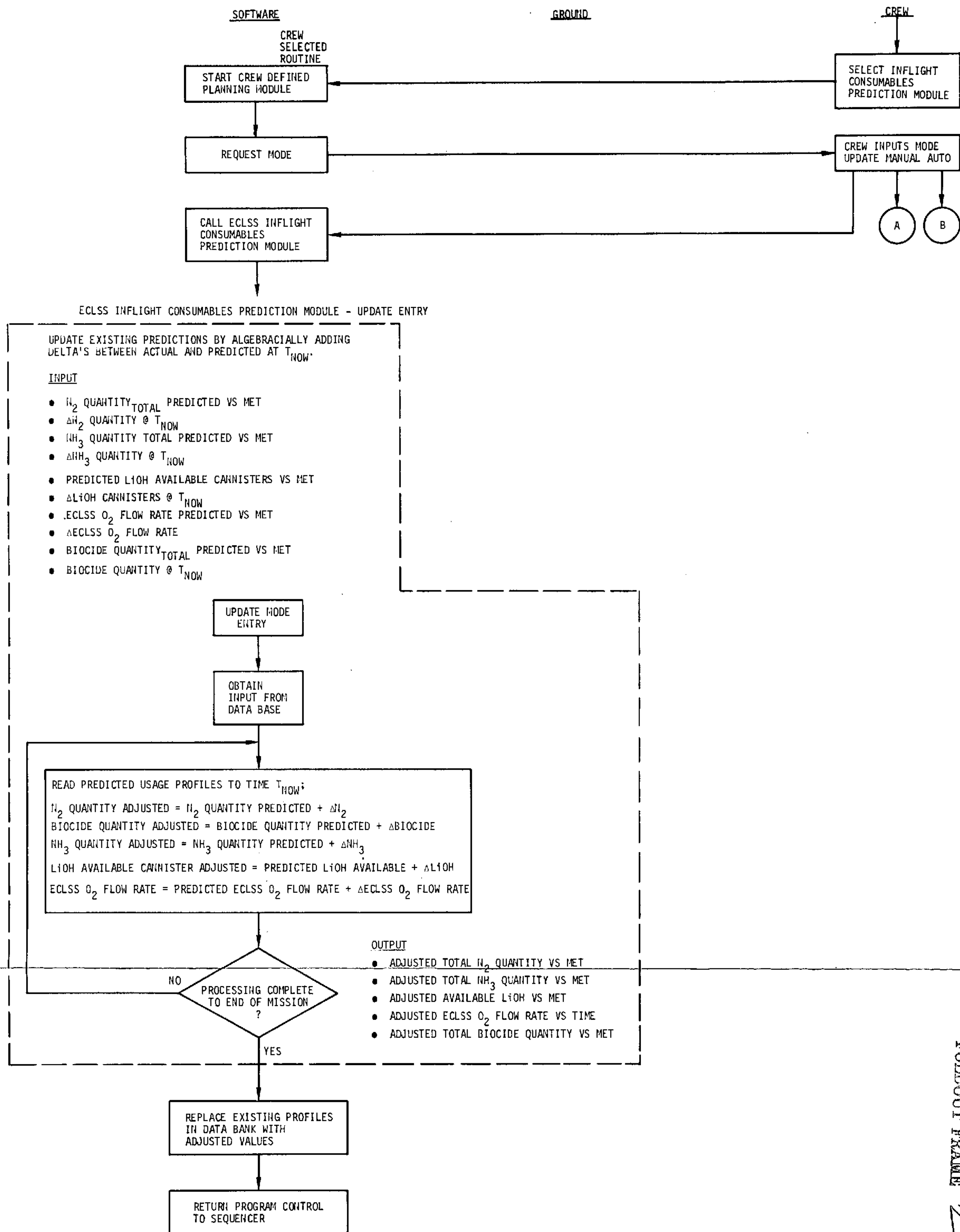


Figure 4.2-2. ECLSS Inflight Monitoring and Evaluation Sequence (Concluded)



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 4.2-3. ECLSS Inflight Consumables Prediction Sequence.

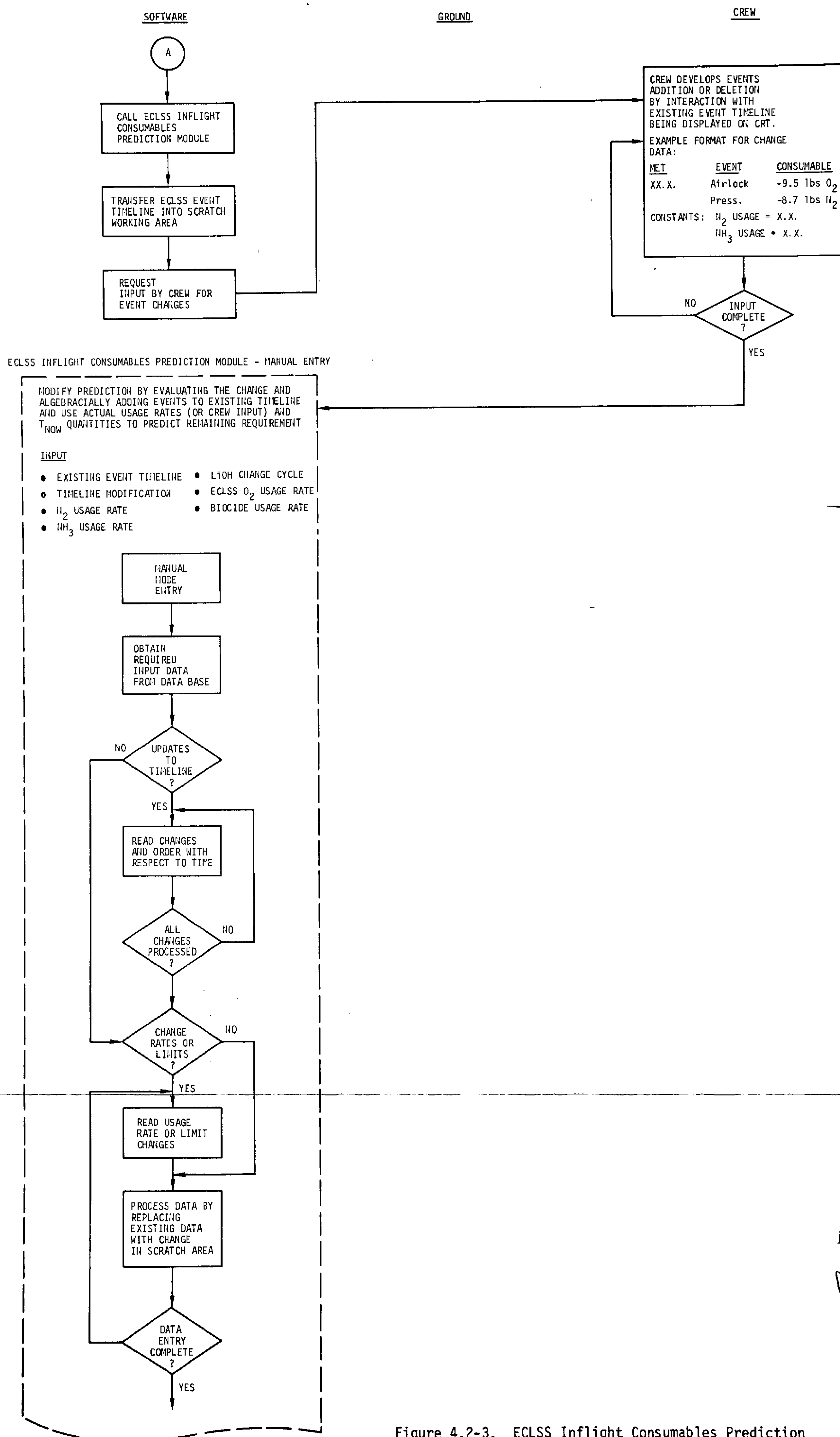


Figure 4.2-3. ECLSS Inflight Consumables Prediction Sequence (Continued).

FOLDOUT FRAME

FOLDOUT FRAME 2

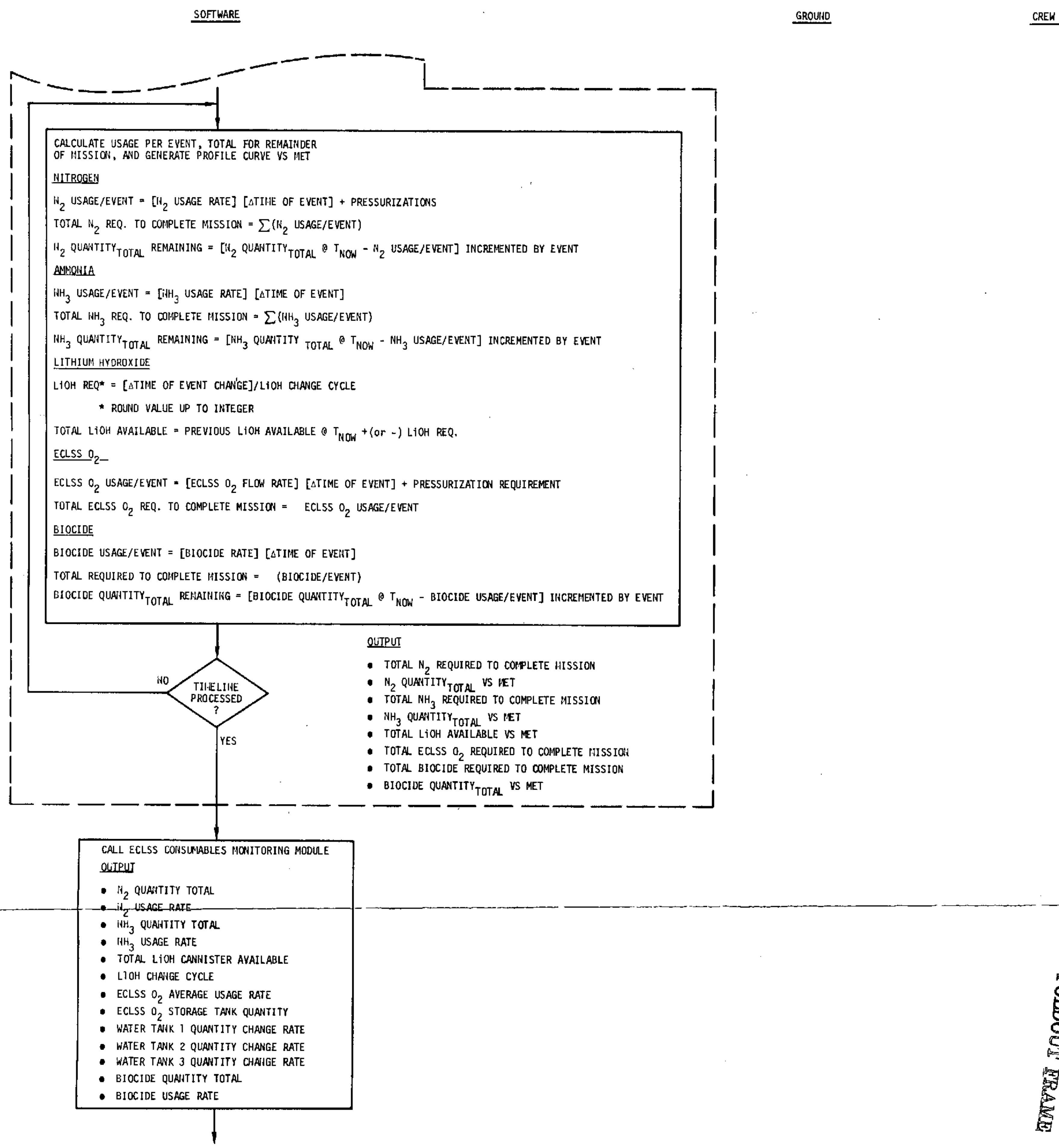
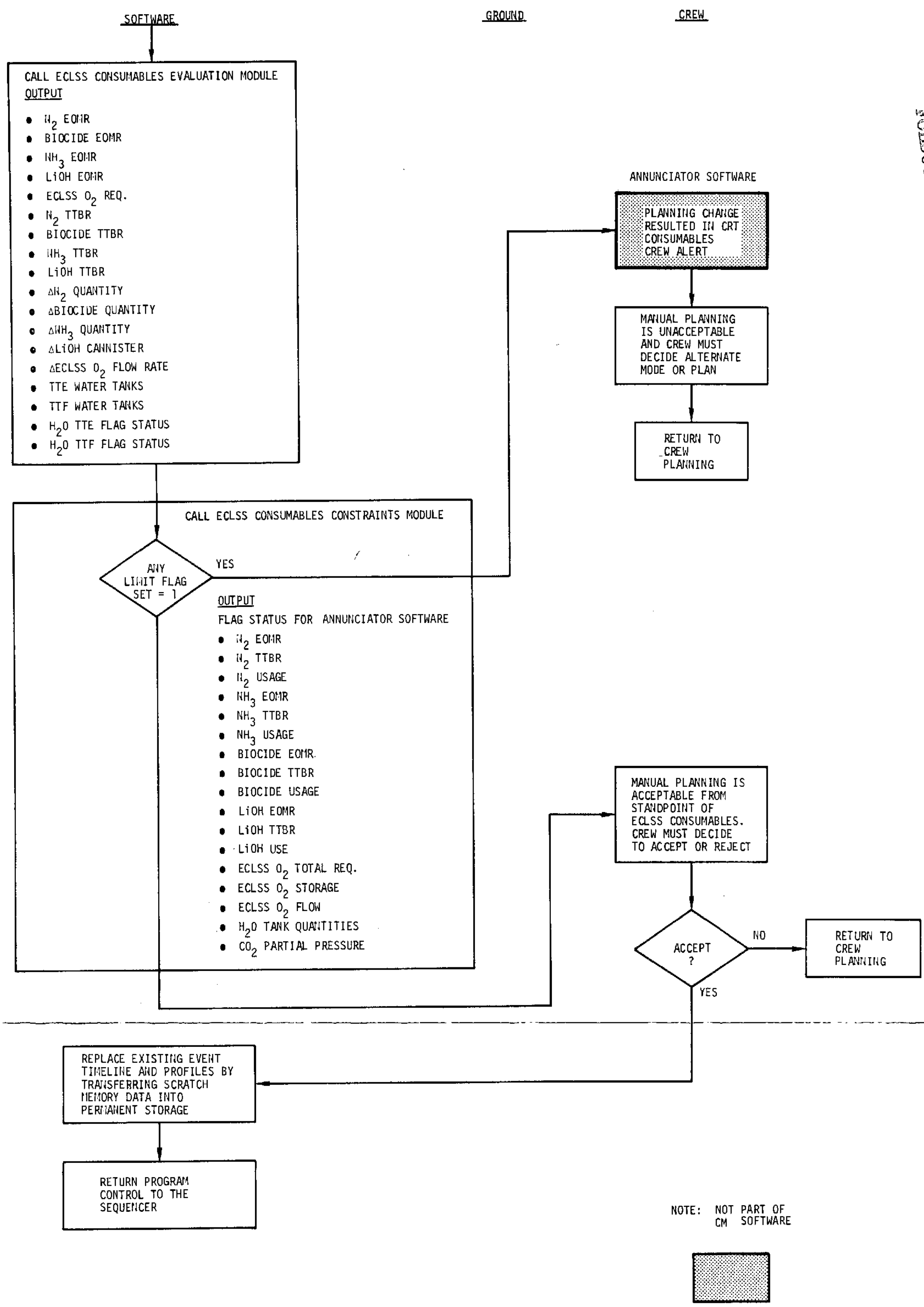


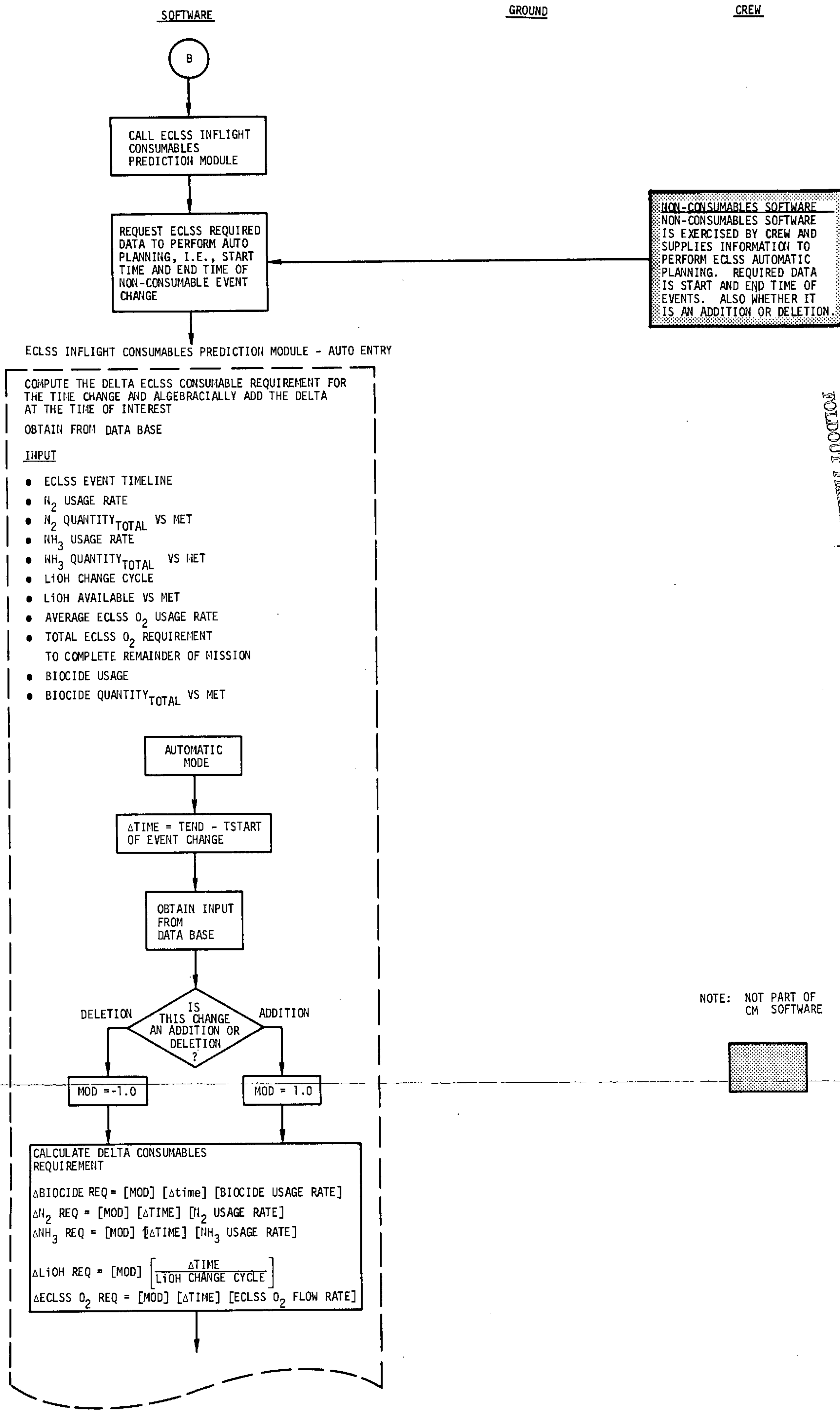
Figure 4.2-3. ECLSS Inflight Consumables Prediction Sequence (Continued).



FOLDOUT FRAME

FOLDOUT FRAME 2

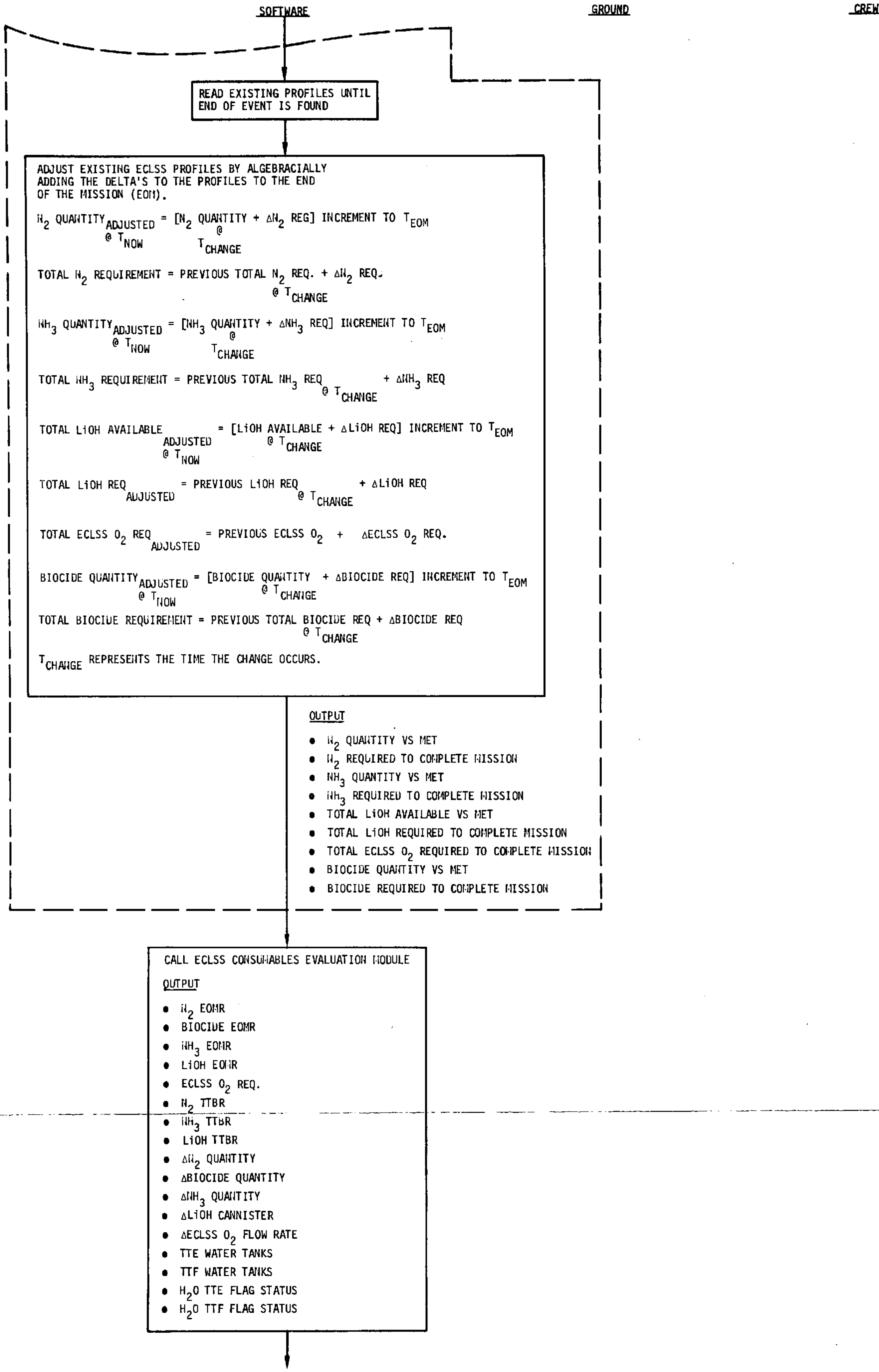
Figure 4.2-3. ECLSS Inflight Consumables Prediction Sequence (Contined).



FOLDOUT FRAME

FOLDOUT FRAME 2

Figure 4.2-3. ECLSS Inflight Consumables Prediction Sequence (Continued).



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 4.2-3. ECLSS Inflight Consumables Prediction Sequence (Continued).

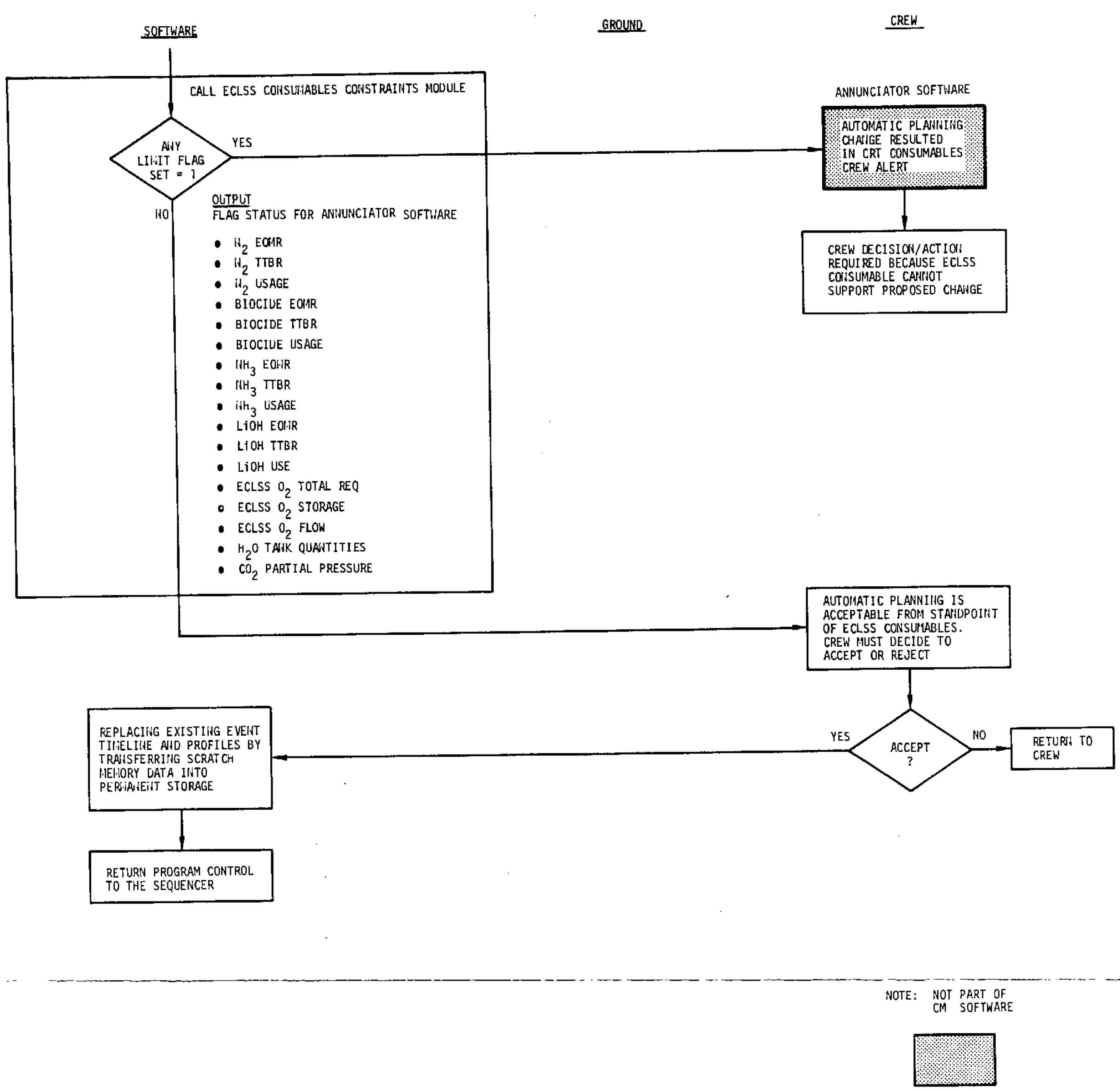


Figure 4.2-3. ECLSS Inflight Consumables Prediction Sequence (Concluded).

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Total Nitrogen Quantity Remaining Profile

A nitrogen usage profile will be provided depicting the predicted total nitrogen quantity remaining versus mission elapsed time with a notation of major nitrogen usage events.

Total Ammonia Quantity Remaining Profile

An ammonia usage profile will be supplied which describes ammonia quantity remaining as a function of mission elapsed time.

Lithium Hydroxide Cannister Data

Number of cannisters required and the cannister replacement cycle will be provided.

Constraints Data

Limit values will be required for end-of-mission reserves of nitrogen, ammonia, and lithium hydroxide. Also, usage rate limits versus mission elapsed time will be required for nitrogen, ammonia, and ECLSS oxygen.

Water Tank Quantities

Values of upper and lower water quantity limits are required. Predicted water dump and sublimation times shall be provided.

Total ECLSS Consumables Requirements

Total quantities required for the planned mission shall be supplied for nitrogen, ammonia, lithium hydroxide, and ECLSS oxygen.

B. Form of Input Data

Typical forms of input data are listed below:

ECLSS Consumables Event Timeline

MET			Usage Rate				Quantity Required			
Start	Stop	Event	O_2	N_2	NH_3	H_2O	O_2	N_2	NH_3	H_2O
XXX	XXX	Radiator Oper.	XX	XX	XX	XX	XX	XX	XX	XX
XXX	XXX	Airlock Oper.	XX	XX	XX	XX	XX	XX	XX	XX
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
XXX	XXX	NH_3 Boiler Oper.	XX	XX	XX	XX	XX	XX	XX	XX

ECLSS Consumables Usage Profiles

MET	Total Quantity Remaining N_2 (lbs)	NH_3 (lbs)
T_1	XX	XX
T_2	XX	XX
.	.	.
.	.	.
.	.	.
T_{EOM}	XX	XX

End-of-Mission Reserve Limits

Consumables	Minimum EOMR
N_2	XX
NH_3	XX
LiOH	XX

Usage Rate Limits

MET	ECLSS O_2	N_2	NH_3
T_1	XX	XX	XX
T_2	XX	XX	XX
.	.	.	.
.	.	.	.
.	.	.	.
T_{EOM}	XX	XX	XX

Water Quantity Cycle

MET Start	Stop	Dump	Sublimation
XX	XX	x	
XX	XX		X
XX	XX		X

ECLSS Total Consumables Requirements

Consumable	Quantity Required
O_2	XX
N_2	XX
NH_3	XX
LiOH	XX

4.2.4.2 ECLSS Consumables Monitoring Data

A. Parameters Required

The ECLSS parameters which are required as inputs to the consumables management software includes the following:

- o Nitrogen quantity for each tank
- o ECLSS Oxygen flow rate
- o Oxygen repressurization-tank quantity
- o Lithium hydroxide cannister replacement cycle
- o Ammonia quantity for each tank
- o Water quantity for each potable water tank
- o Biocide tank quantity

B. Measurement Technique

Nitrogen and Oxygen Gas Quantities

An approximation of gas quantity can be obtained by using pressure measurements and assumed temperature values to calculate quantity. This technique is appropriate for applications involving well defined temperature variations as a function of time. Such is not always the case for space vehicle applications and the resulting inaccuracy is excessive for consumables management purposes.

Gas quantity calculations using pressure and temperature measurements (PVT gauging) provides acceptable accuracy for determining nitrogen and oxygen tank quantities.

Gas density measurements (ρV gauging) provide good accuracy for quantity determination. The accuracy of the ρV gauging technique is attractive because the overall consumables management accuracy is improved by utilizing this technique.

Water, Ammonia, and Biocide Quantities

Highly accurate measurements of water, ammonia, or biocide are not required for consumables management purposes, therefore, a simple, reliable gauging technique should be utilized. The sophistication of a nuclear gauging system, or even a capacitance gauge, is probably not justifiable.

Bladder displacement, indicated by a potentiometer output signal, can be related to consumable quantity to an acceptable degree of accuracy for management of these consumables.

Lithium Hydroxide Cannisters

An inventory of lithium hydroxide cannisters available is required by the consumables management software. The inventory can be maintained by providing an indication to the computer each time a cannister is replaced. The replacement indication may be provided automatically, by an arrangement such as an electromechanical counter, or manually by crew input. Although an automatic device is desirable because it is less subject to error, the manual entry technique is adequate for maintaining a cannister inventory.

ECLSS Oxygen Flow Rate

Direct measurement of gas flow can be accomplished by momentum transfer or heat transfer gauging techniques, both of which are currently operational. The momentum transfer technique normally implies greater instrument complexity. Heat transfer gauging techniques are commonly employed for gas flow rate measurement and can provide a reasonably accurate measurement for ECLSS consumables management.

4.2.4.3 ECLSS Crew Displays

A. Display Data

ECLSS consumables management data to be provided for crew display include constraint violation indications and consumables status data. Any limit value violation detected by the consumables management software will result in a signal being produced to activate a crew alert indicator.

Consumables status data displays selectable by crew option should include quantity and usage rate information for the ECLSS consumables nitrogen, ammonia, oxygen, lithium hydroxide, biocide, and water.

B. Display Type

- Graphical Displays - The ECLSS consumables usage profiles should be displayed in graphical form which presents quantity versus mission elapsed time. Consumables data requiring graphical profile display formats include total nitrogen quantity remaining and total ammonia quantity remaining.
- Tabular Displays - ECLSS consumables data to be displayed in tabular formats are indicated below. The indicated form is typical of data tables which might be employed by the crew in performing consumables management.

NITROGEN

Total Quantity

Actual	Predicted	Δ
XXX	XXX	XX

EOMR

Predicted	Limit	Δ
XXX	XXX	XX

Tank	Quantity	Rate
1	XX	XX
2	XX	XX
.	.	.
.	.	.
.	.	.
N	XX	XX

OXYGEN

Flow Rate		Quantity Required to EOM	Repress Tank Quantity	
Actual	Predicted		Actual	Predicted
XX	XX	XXX	XXX	XXX

LITHIUM HYDROXIDE

Cannisters Available	Cannisters Required to EOM	EOMR
XX	XX	X

AMMONIA

Total Quantity			Tank	Quantity	Rate
Actual	Predicted	Δ			
XX	XXX	XX	1	XX	X
			2	XX	X
			3	XX	X

EOMR		
Predicted	Limit	EOMR
XX	XX	XX

POTABLE WATER

Tank	Quantity	Rate	Time to Full	Time To Empty
1	XX	XX	XXX	XXX
2	XX	XX	XXX	XXX
3	XX	XX	XXX	XXX

BIOCIDE

Total Quantity

Actual	Predicted	Δ
XXX	XXX	XX

Tank	Quantity	Rate
1	XXX	XX
2	XXX	XX

EOMR

Predicted	Limit	Δ
XXX	XXX	XX

4.2.5 ECLSS Consumables Management Software Estimates

Sizing estimates were prepared for the ECLSS consumables management software shown in flow chart form in Figures 4.2-1, -2, and -3. A summary of both the fixed and dynamic data storage estimates are presented for each functional module in Table 4.2-1.

A. Dynamic Data Storage Estimates

The total storage required for the gound supplied prelaunch data entries and the consumables status data retained during flight comprises the dynamic data storage.

For purposes of estimating the storage requirements of the ground supplied data, it was assumed that twelve ECLSS events would be required on the timeline, that three hundred and sixty points are required to define the nitrogen profile, that one hundred and eighty points are required for the ammonia profile, and that ninety points are required for the water quantity cycle. These are the major items required for storage of ECLSS ground supplied data.

The consumables status data required for display purposes, as described in Section 4.2.4.3, comprises the majority of the inflight acquired data to be stored.

B. Fixed Data Storage Estimates

Fixed data storage estimates for the functional modules were prepared by estimating the software required for performing the operations in the ECLSS consumables management algorithms. Requirements for temporary storage of instructions and variables are included in the estimates shown.

Table 4.2-1 ECLSS Consumables Management Software Sizing Estimates

MODULE	FIXED STORAGE (words)	DYNAMIC STORAGE (words)
Prediction	40	3025
Monitoring	85	15
Evaluation	95	20
Constraints	65	15
Inflight Prediction	270	50

4.3 FUEL CELL AND CRYOGENIC STORAGE (FCCS)

The function of the FCCS is to supply electrical power for operation of orbiter equipment during all mission phases from prelaunch through landing. There are three hydrogen/oxygen fuel cell power plants to which reactants are supplied from two hydrogen and two oxygen dewar type storage tanks. In addition, the ECLSS oxygen is supplied from the cryogenic oxygen supply. Water is generated as a by-product of fuel cell operation and is supplied to the ECLSS for storage and management.

The mandatory nature of the FCCS functions places a high priority on management of the cryogens in order to assure that adequate supplies are available to complete the mission as scheduled.

4.3.1 FCCS Consumables Management Functions

The consumables required for FCCS operation are cryogenic oxygen and hydrogen. Reactant usage rates are dependent on 1) electrical power generation requirements, 2) fuel cell purge requirements, and 3) ECLSS oxygen usage rate. Management of ECLSS oxygen usage is a function of the ECLSS consumables management software. Control of FCCS reactant usage is accomplished by control of electrical loads; this has two beneficial effects from a consumables management standpoint. First, the reactant flow rates are directly proportional to electrical power loads, and second, the fuel cell purge frequency is directly proportional to reactant flow rates.

The consumables management functions proposed for FCCS onboard consumables management include full capability for performing monitoring, evaluation and prediction of cryogen usage. Capability is also included for inflight prediction and evaluation of cryogen requirements for proposed revisions to an existing mission plan.

4.3.2 FCCS Concept Selection Considerations

There are several factors which influenced selection of the FCCS consumables management concept which incorporates functional capability for monitoring, evaluation, prediction, and inflight replanning of reactant usage. The mandatory requirement for FCCS operation during all mission phases places high priority on assuring that adequate reactants are available to complete a planned mission. The capability which exists to control reactant usage can be utilized to maintain reactant usage rates at levels which ensure that end-of-mission reserve limits are not violated thus assuring adequate consumables will be available for FCCS operation throughout the mission.

Preliminary studies indicate that FCCS consumables will be in limited supply which implies that management by excess* is not a luxury that will be available for cryogen management. This fact imposes a requirement for actively managing reactant usage; the information provided by the proposed consumables management concept will assist the crew in selective assignment of electrical power loads in order to effectively utilize the available consumables.

Flexibility in adding, deleting, and rescheduling mission events is required if maximum benefit is to be derived from each Shuttle mission. Provision for attaining such flexibility requires that the impact on consumables usage be evaluated. In particular, FCCS consumables usage must be evaluated since many mission revisions will significantly affect cryogen consumption. The onboard consumables management replanning provisions can ensure that flexibility in mission performance is supported without having to rely completely on ground support for evaluation of effects on cryogen usage.

4.3.3 FCCS Onboard Software Description

The FCCS consumables management software provides for onboard monitoring, evaluation, and replanning of cryogenic oxygen and hydrogen usage. Ground support premission planning data provides both the consumables event timeline and FCCS consumables constraint data for processing and storage in the onboard software. The capability then exists throughout the mission for monitoring FCCS actual consumables status data, comparing actual usage with predicted usage, performing parameter tests for limit value violations, predicting end-of-mission reserve quantities,

* "Management by excess" refers to a technique whereby the consumable storage quantity far exceeds the maximum anticipated usage.

and modifying the consumables usage plan in accordance with mission revisions. The same onboard consumables management software is utilized for the prelaunch and the inflight monitoring and evaluation sequences which are described in the paragraphs which follow.

Prelaunch Analysis and Evaluation

Functional software flow for the FCCS consumables management prelaunch operations is shown in Figure 4.3-1. The ground support system provides data for processing and storage in the onboard consumables management software. The ground supplied input data includes the consumables event timeline, consumables constraints data, and cryogen loading requirements. The consumables event timeline is processed and calculations are performed in the Consumables Prediction Module to provide hydrogen and oxygen usage profiles as well as total quantities required for the planned mission. Hydrogen and oxygen predicted end-of-mission reserves are calculated in the Evaluation Module and tested against end-of-mission reserve limit values in the Constraints Module.

A constraint violation will produce a signal to activate an alert indication to the ground support complex. If no constraint violations were indicated, program control would be returned to the sequencer. However, detection of a violation would indicate that a diagnostic procedure should be initiated. Possible causes of a limit value violation include inadequate quantities of cryogen loaded, an error in the consumables event timeline, or an error in the consumables management software.

Inflight Monitoring and Evaluation

Functional software flow for the inflight monitoring and evaluation of FCCS reactant usage is shown in Figure 4.3-2. The Monitoring Module, Evaluation Module, and Constraints Module are utilized in performing this sequence of operations.

The Monitoring Module utilizes cryogen quantity measurements to calculate hydrogen and oxygen usage rates per tank and to calculate tank balance information.

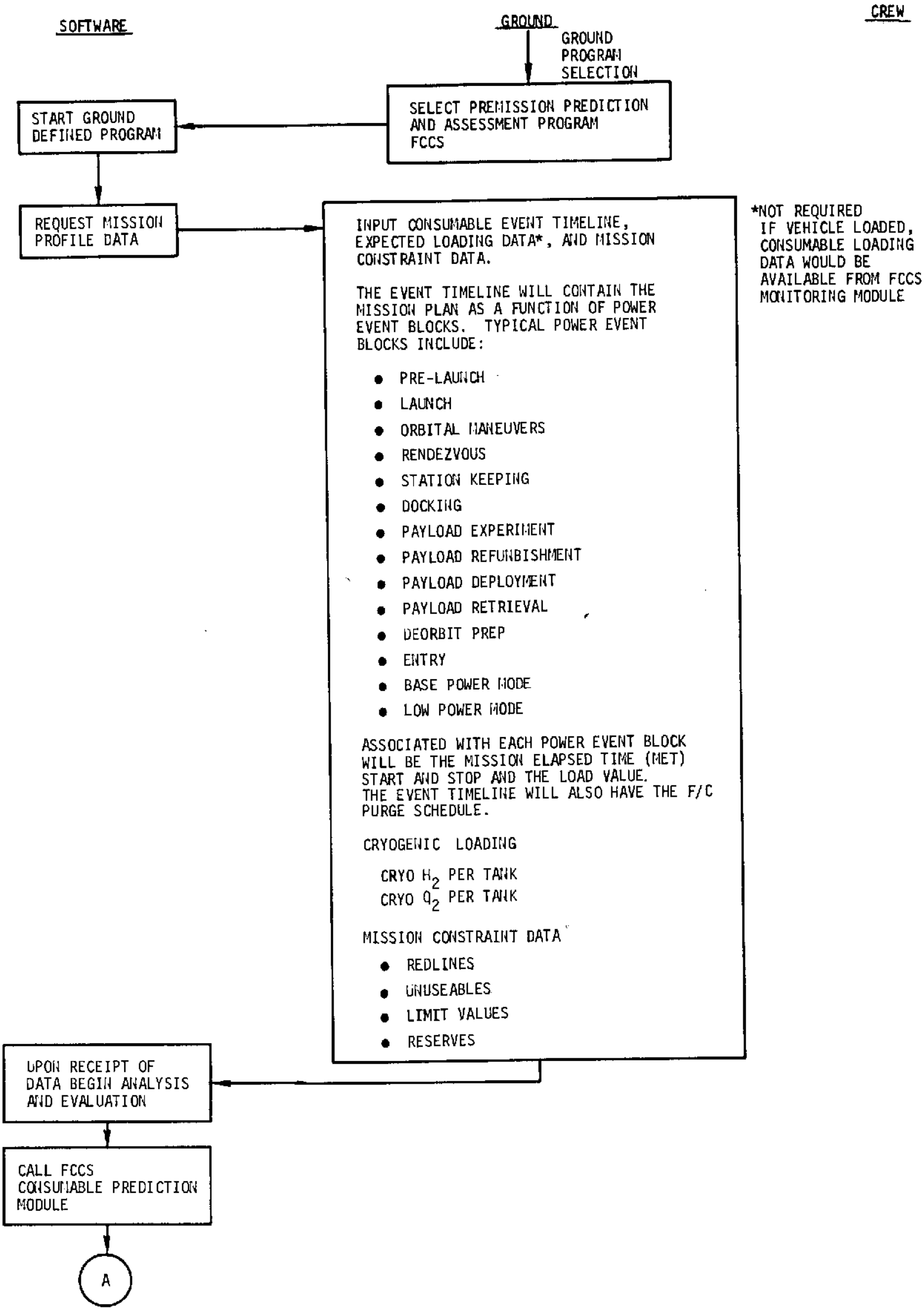


Figure 4.3-1. FCCS Prelaunch Analysis and Evaluation Sequence

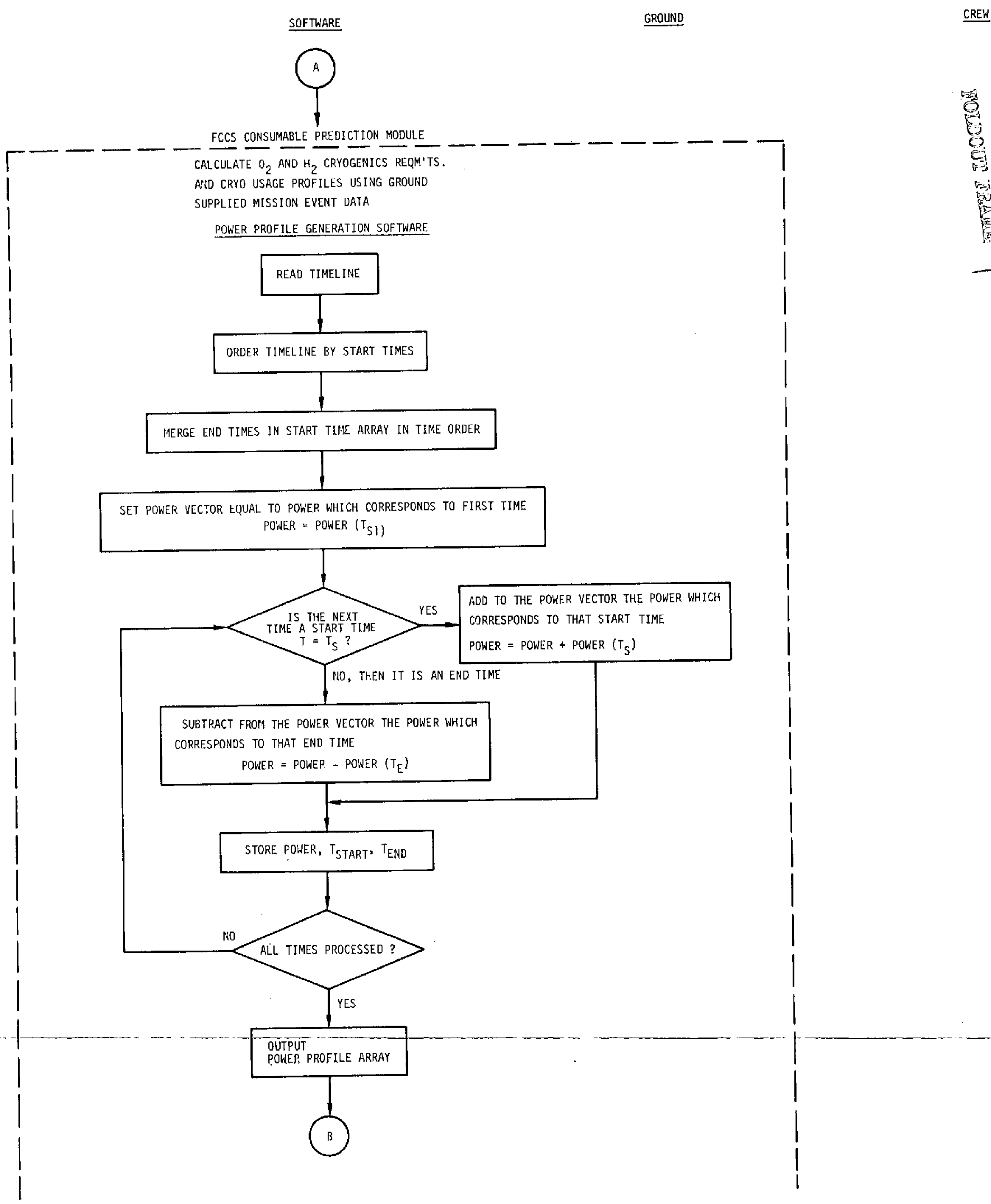


Figure 4.3-1. FCCS Prelaunch Analysis and Evaluation Sequence (Continued).

FOLDOUT FRAME 1
FOLDOUT FRAME 2

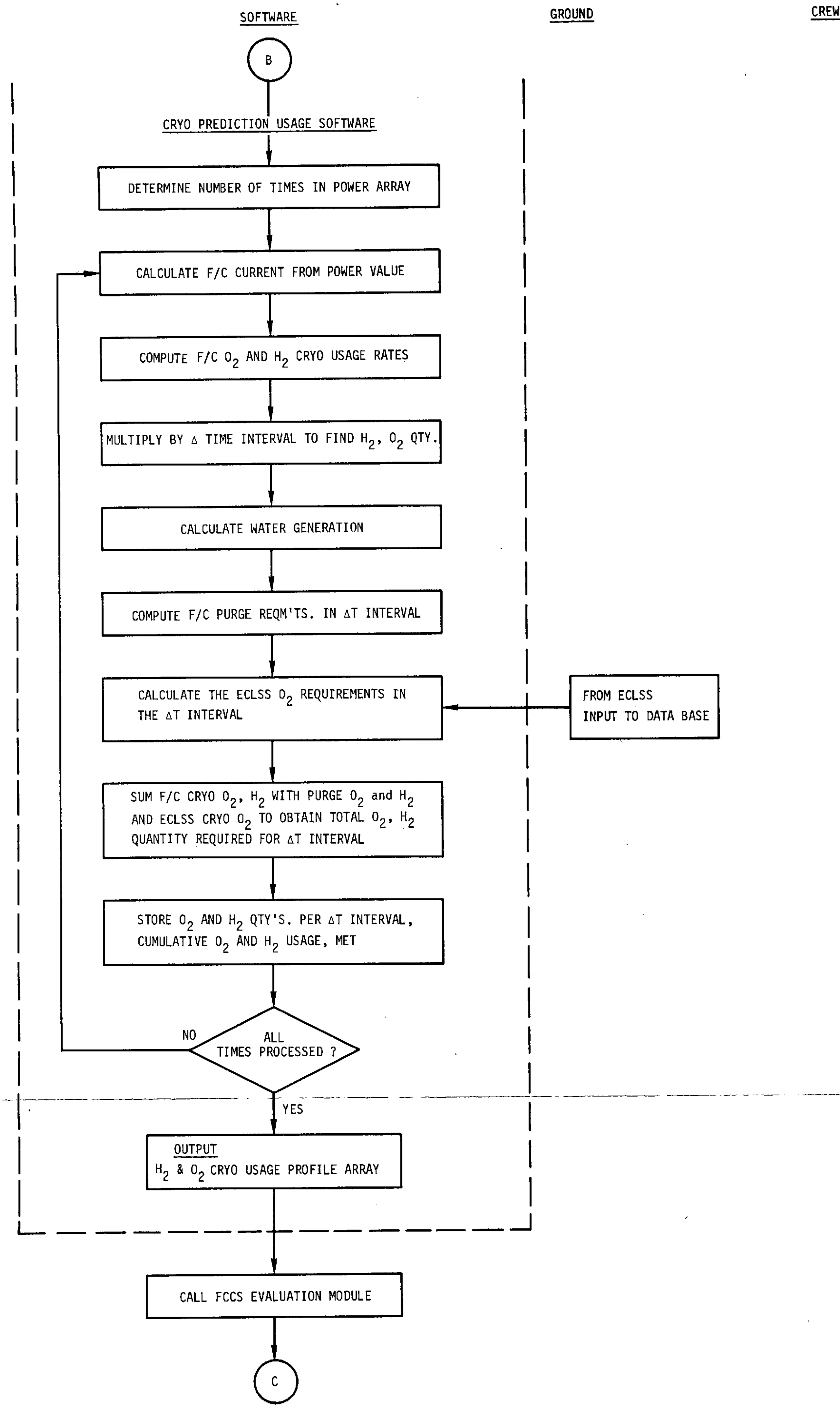


Figure 4.3-1. FCCS Prelaunch Analysis and Evaluation Sequence (Continued).

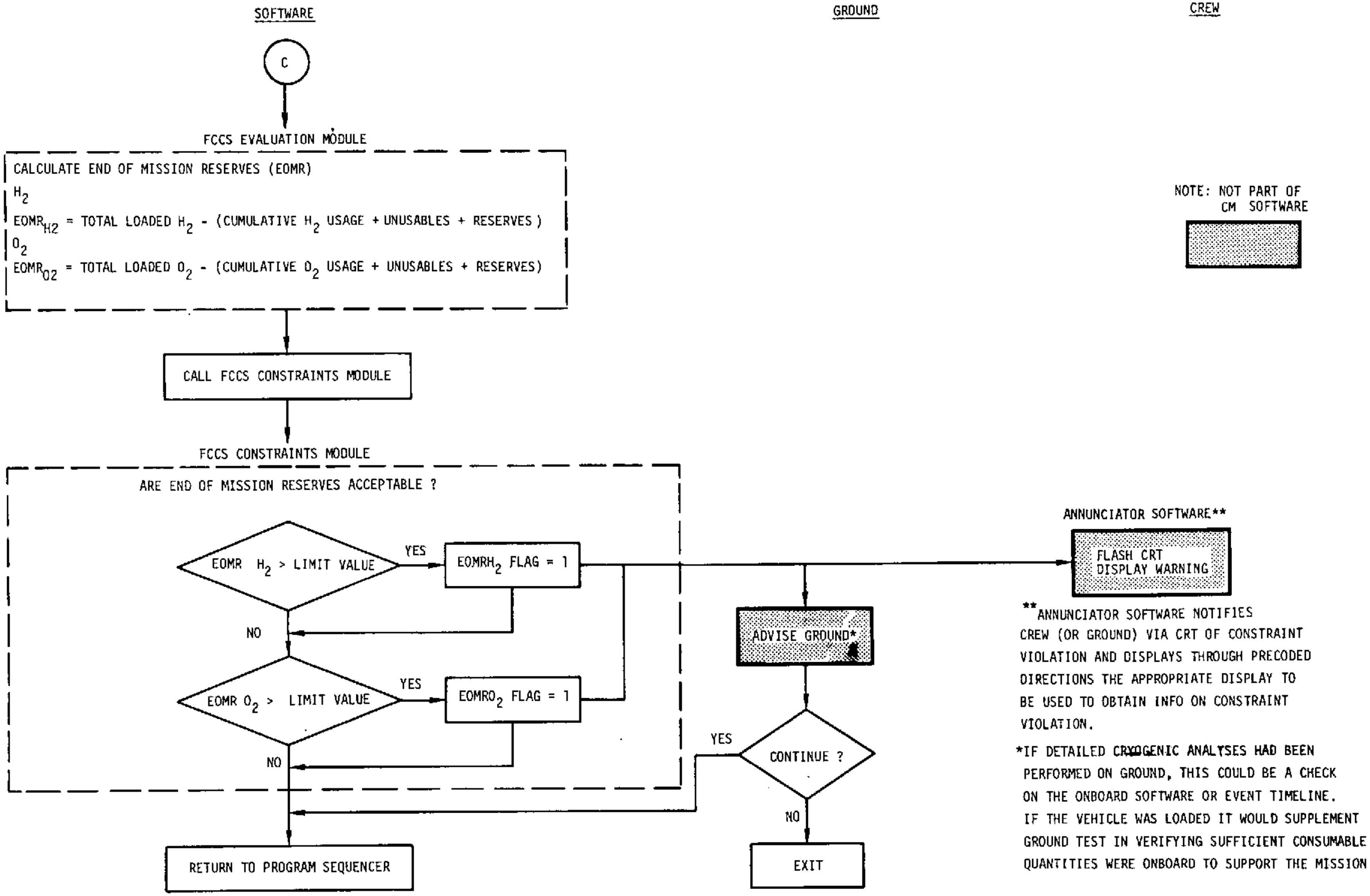
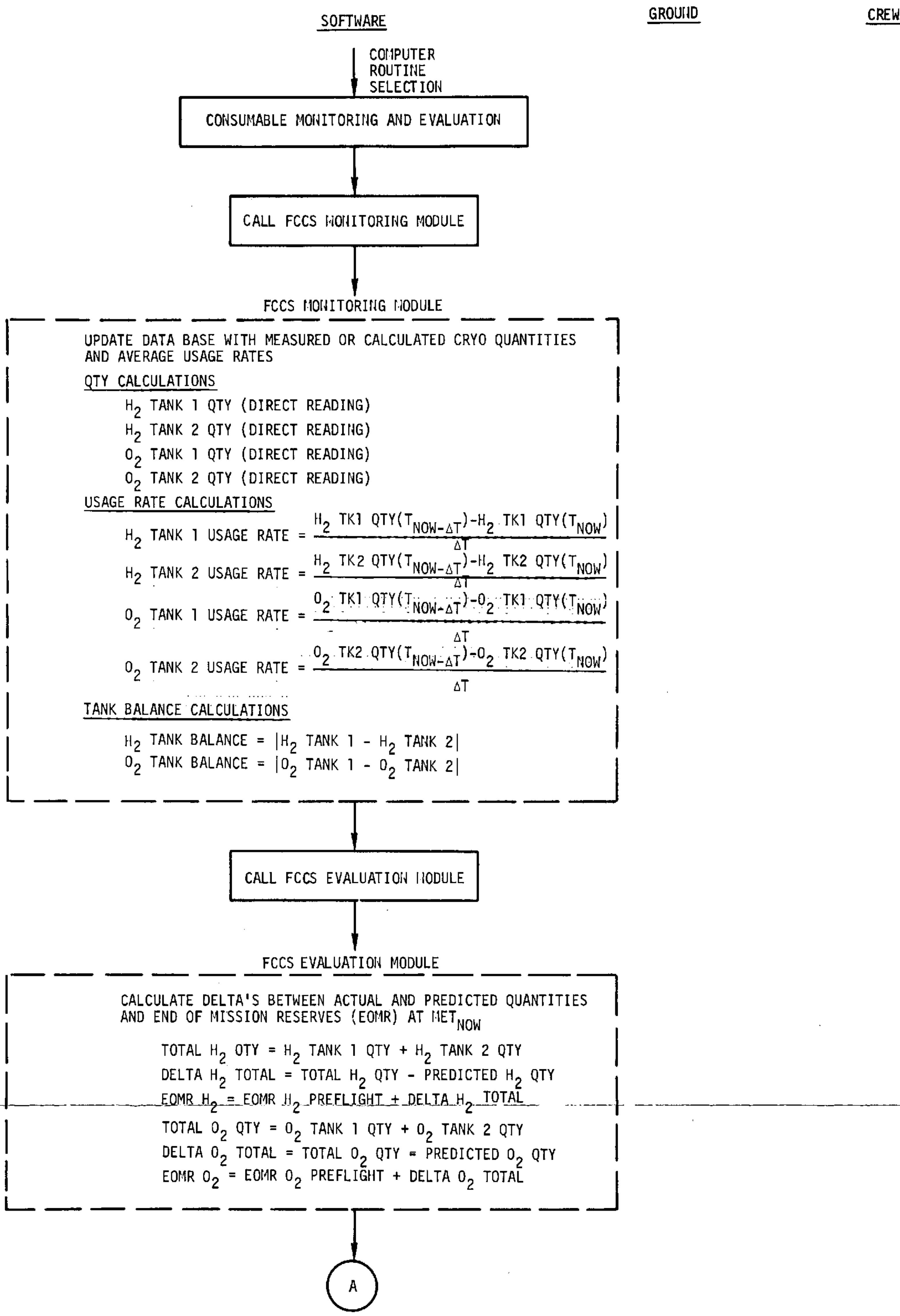


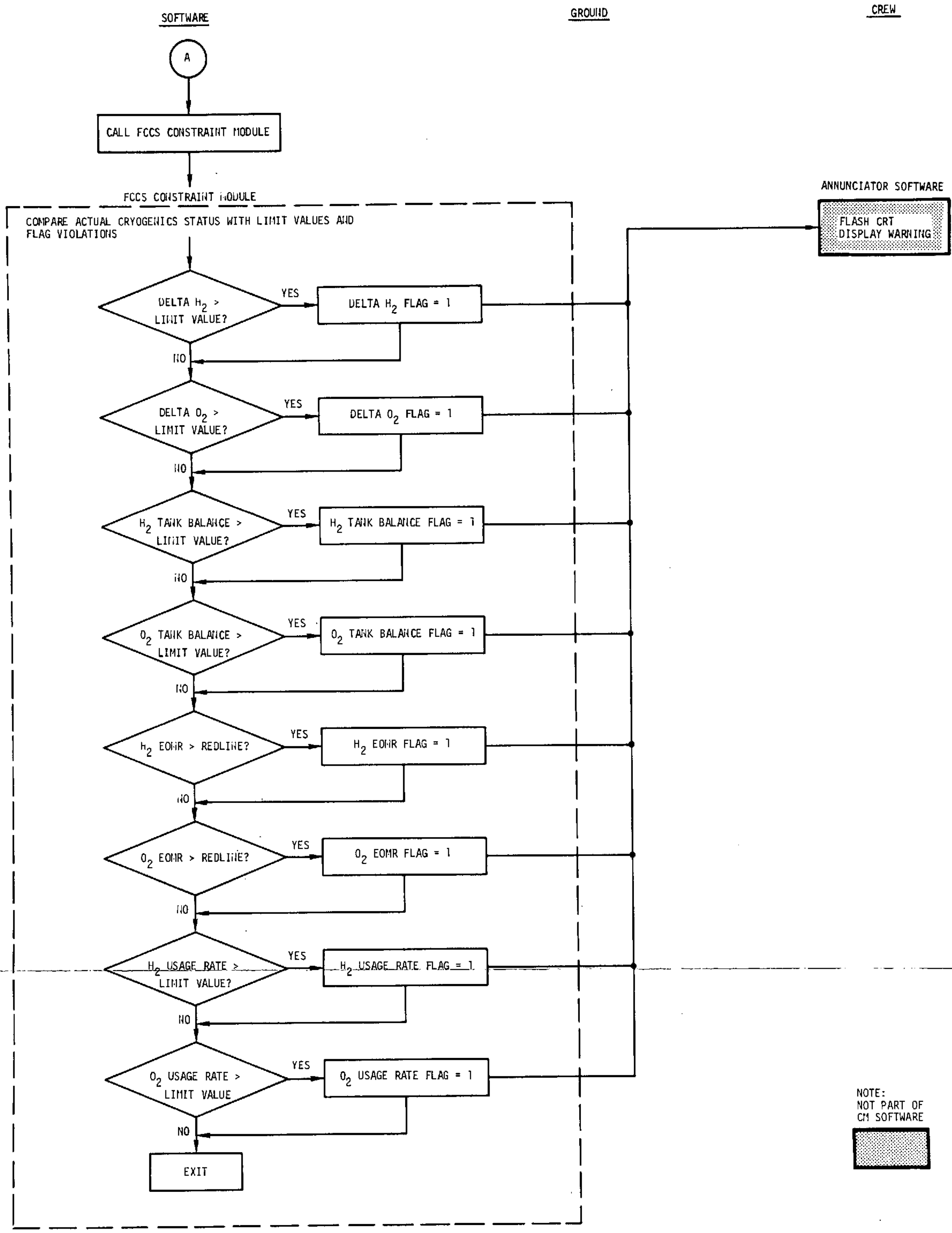
Figure 4.3-1. FCCS Prelaunch Analysis and Evaluation Sequence (Concluded).

FOLDOUT FRAME 1



FOLDOUT FRAME 2

Figure 4.3-2. FCCS Inflight Monitoring and Evaluation Sequence.



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 4.3-2. FCCS Inflight Monitoring and Evaluation Sequence (Concluded).

End-of-mission reserve quantity predictions are updated by Evaluation Module calculations. The total cryogen quantities remaining and the predicted ECLSS oxygen requirements are used in the calculations.

The Constraints Module is used to test status data for limit value violations of actual versus predicted quantities, tank balance, end-of-mission reserves, and usage rates. An end-of-mission reserve violation is based on predicted usage and therefore, may be interpreted as an advance warning of potential problems later in the mission. The remaining constraints are based on current conditions which require attention. A constraint violation will produce a signal to activate a crew warning indication in order that the crew may take subsequent corrective action.

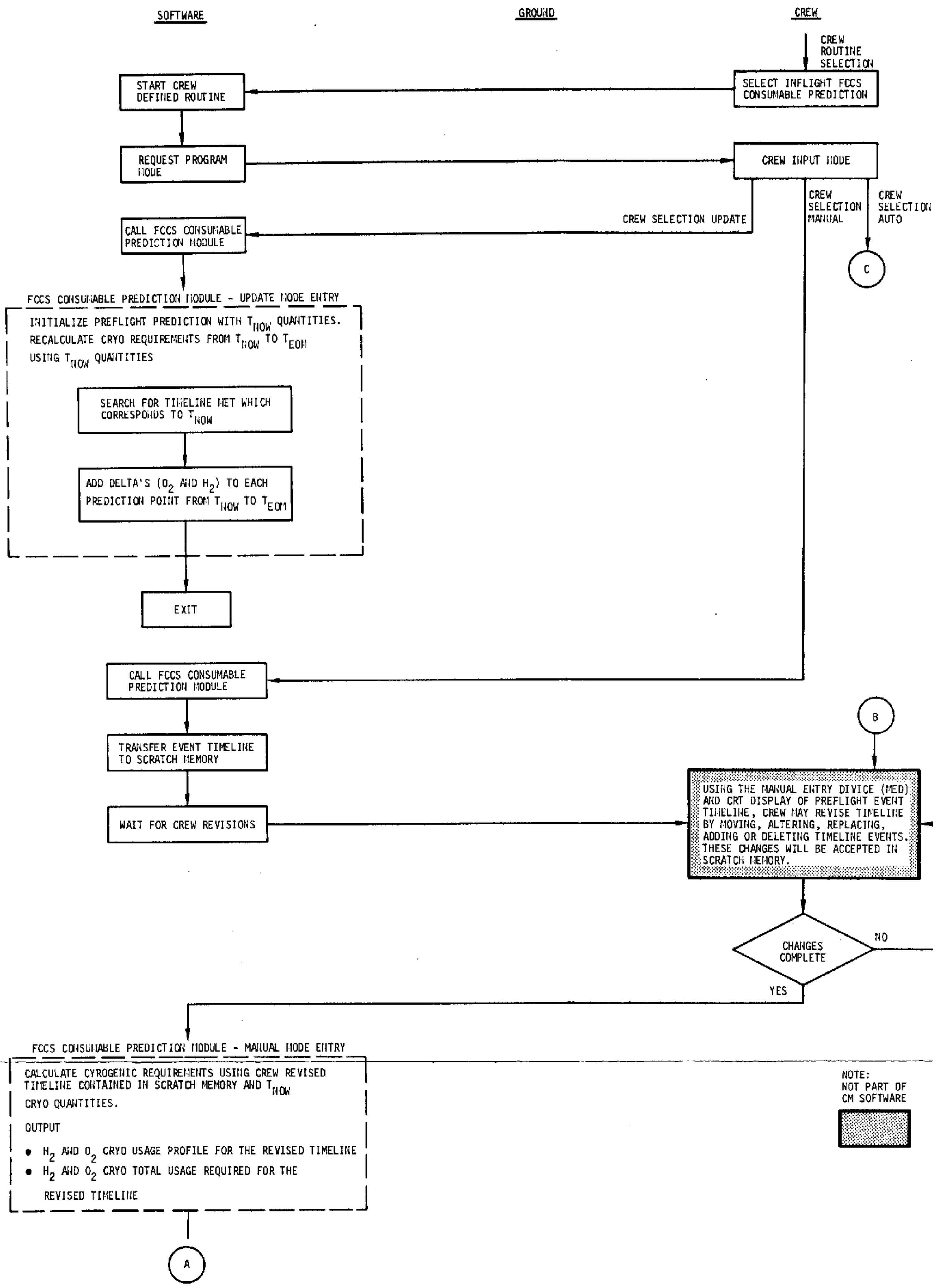
Inflight Consumables Prediction

The FCCS inflight consumables prediction sequence utilizes the Monitoring Module, Evaluation Module, Prediction Module, and Constraints Module as is shown by the functional software flow in Figure 4.3-3. This sequence is similar in operation to the prelaunch analysis and evaluation sequence described previously.

Three optional features of the inflight prediction sequence which may be selected by the crew include prediction updates, predictions using manual mode entries, and predictions using automatic mode entries.

The prediction update function is designed to initialize the predicted reactant usage profiles to coincide with actual status at the current time, T_{NOW}. The prediction update is designed to shift the predicted usage profiles so that the actual and predicted values are in agreement at the update time. This feature will make it easier for the crew to assess the significance of predicted consumables usage for the remainder of the planned mission.

Cryogen usage predictions may be initiated by crew manual entry of consumables event timeline revisions. Revisions may consist of adding, deleting, or rescheduling event timeline data. Calculations are performed in the consumables Prediction Module to determine hydrogen and

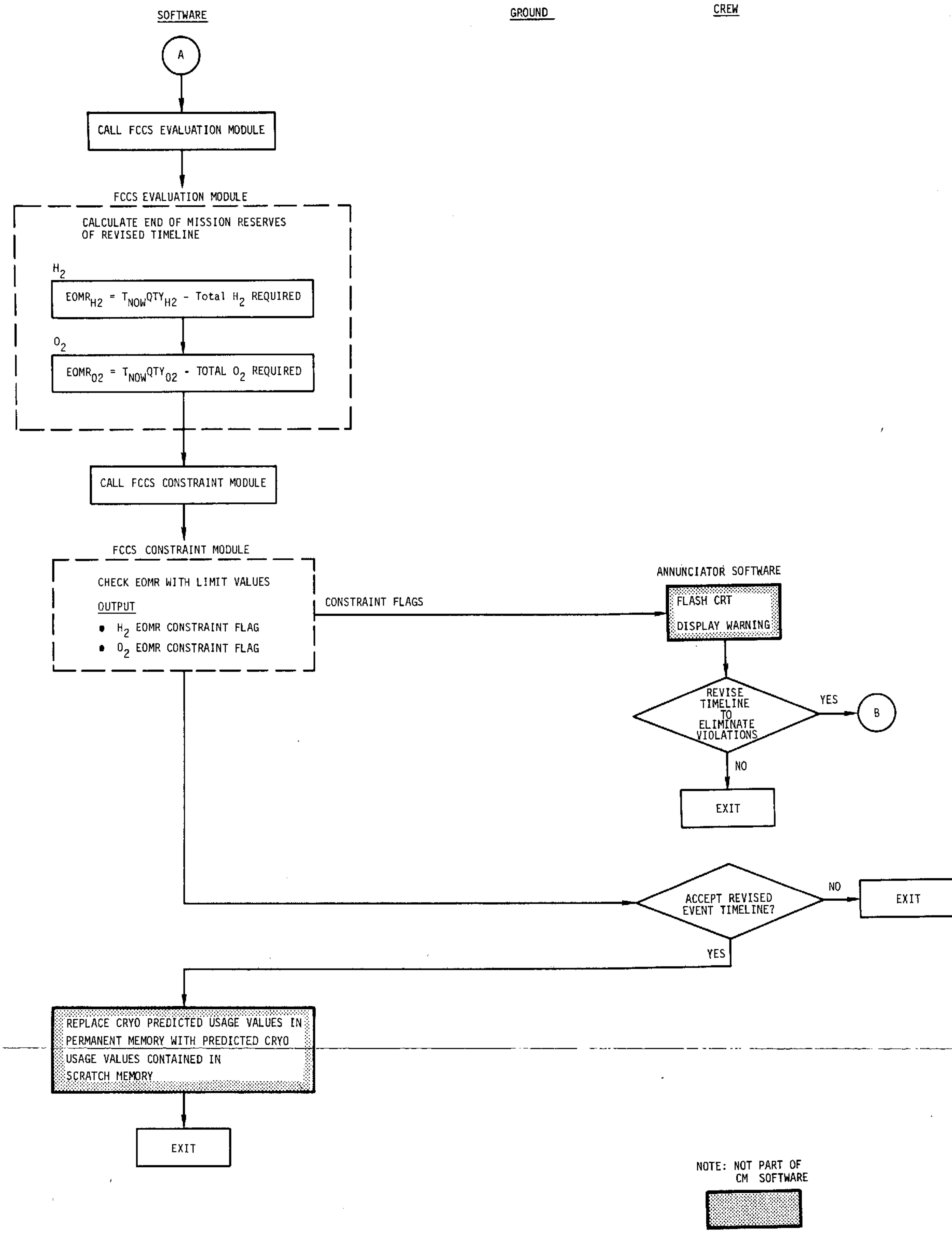


FOLDOUT FRAME

FOLDOUT FRAME

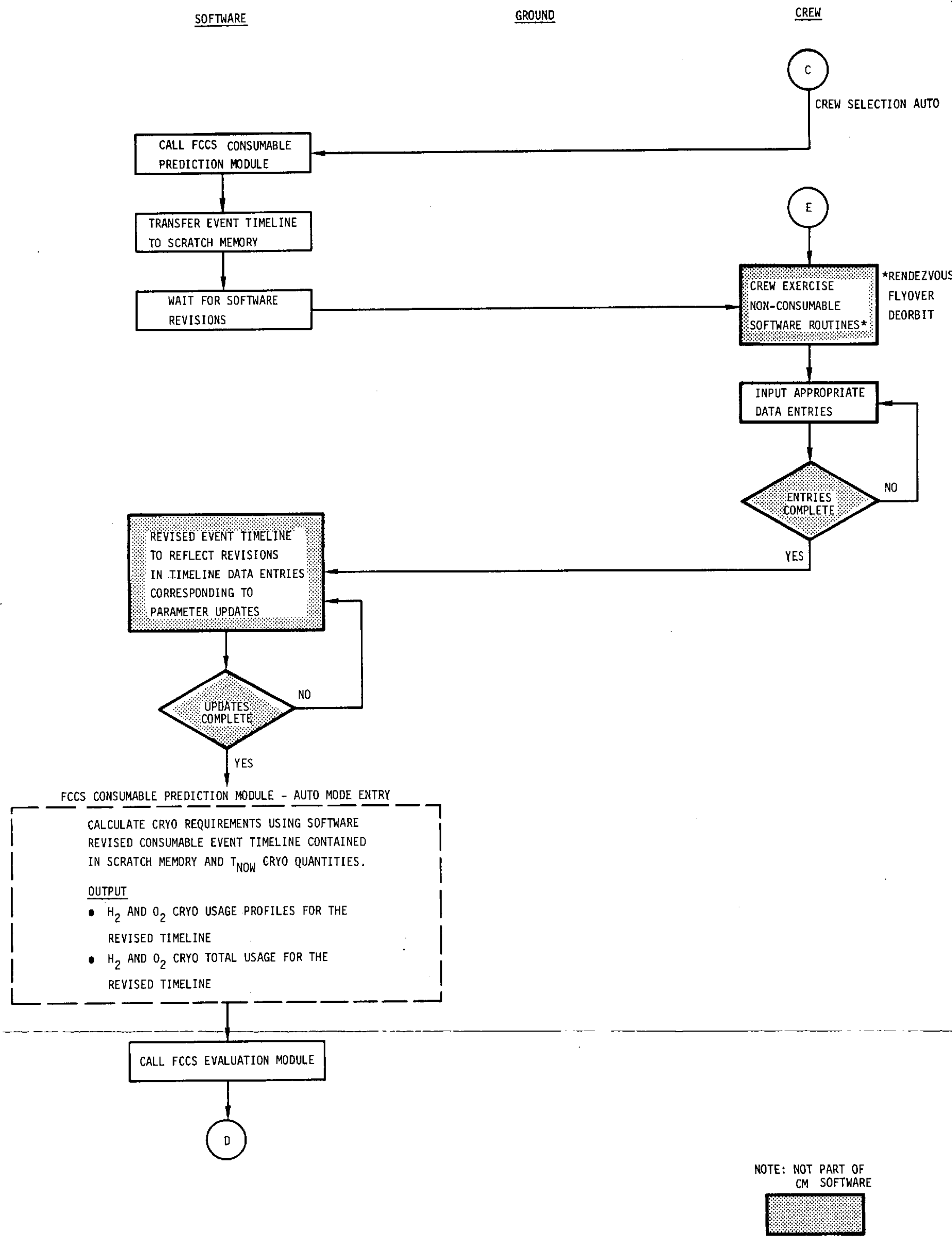
Figure 4.3-3. FCCS Inflight Consumables Prediction Sequence.

FOLDOUT FRAME 1



FOLDOUT FRAME 2

Figure 4.3-3. FCCS Inflight Consumables Prediction Sequence (Continued).



FOLDOUT FRAME

FOLDOUT FRAME

Figure 4.3-3. FCCS Inflight Consumables Prediction Sequence (Continued).

FOLDOUT FRAME 1

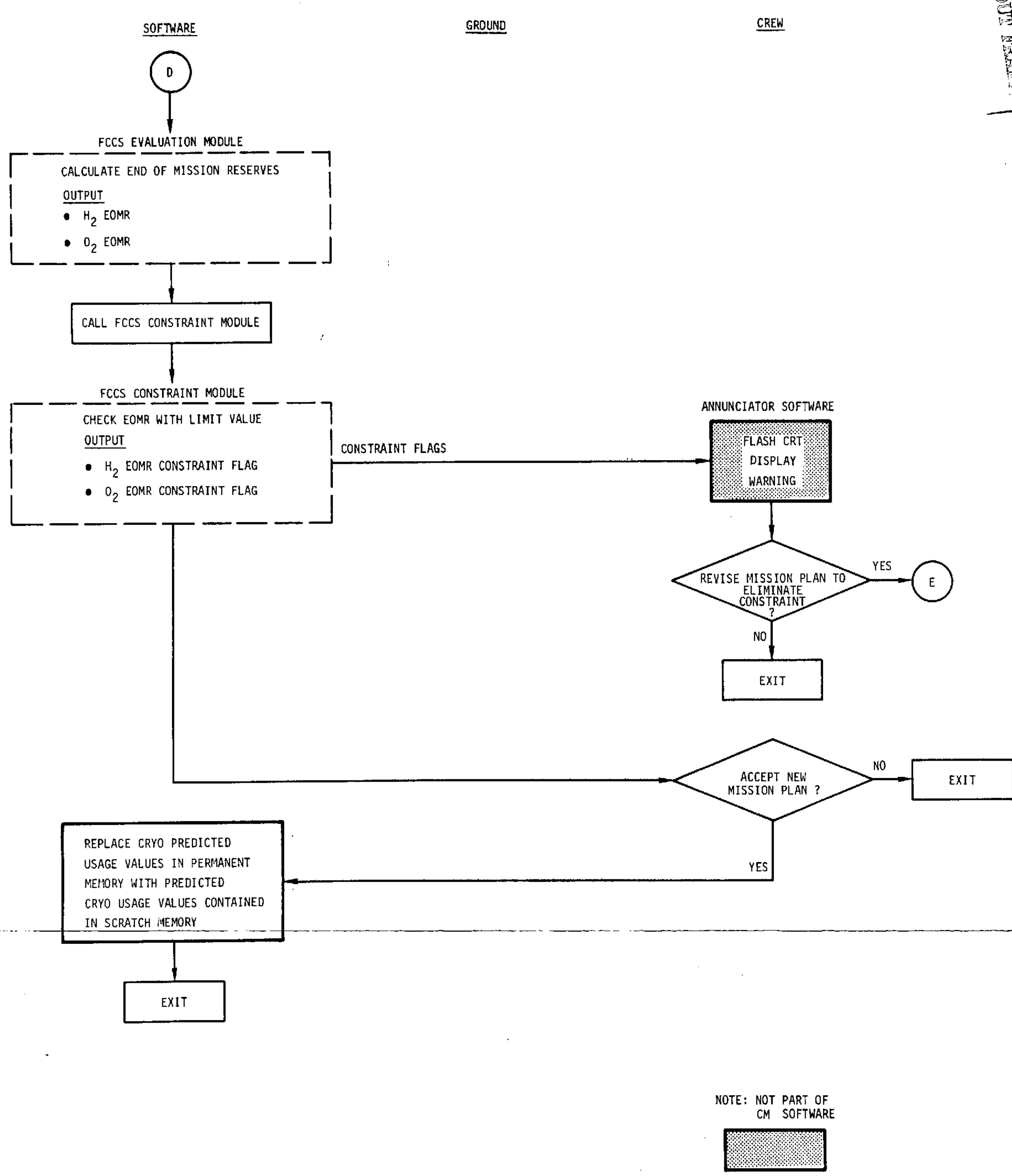


Figure 4.3-3. FCCS Inflight Consumables Prediction Sequence (Concluded).

FOLDOUT FRAME 2

oxygen usage profiles, total usage, and end-of-mission reserve quantities. End-of-mission reserve values are tested in the Constraints Module for limit value violations. Trial revisions may be performed and placed in temporary storage for evaluation prior to selecting an acceptable plan for permanent storage as the current plan.

Prediction revisions may be performed by automatic entry of consumables event timeline revisions for certain limited types of mission revisions such as rendezvous and deorbit maneuvers. These mission revisions involve computations performed by the G&N software which may provide the necessary information for automatic entry of data to revise the consumables event timeline. Subsequent processing of event timeline revisions are identical to that described for the manual entry prediction sequence.

4.3.4 FCCS Input/Output Data Description

4.3.4.1 Mission Description Data

A. Input Data Required

The FCCS input data consists of an event timeline which contains the mission plan as a function of power event blocks, cryogen loading values, and cryogen constraint data such as redlines, parameter limit values, and end-of-mission reserve limits.

Power Event Blocks - Preliminary studies indicate the feasibility of describing the mission profile in terms of electrical power event blocks. The blocks of electrical power are related to mission events for which power requirements have been defined. The following are typical of power event blocks to be included:

- Prelaunch
- Launch
- Orbital Maneuver
- Rendezvous
- Stationkeeping
- Docking
- Payload Experiment

- Payload Deployment
- Payload Retrieval
- Deorbit Preparation
- Entry/Landing
- Base Load - Nominal
- Base Load - Low
- Base Load - Contingency

Basically, there are two methods of using these blocks to describe the mission. The first method is to determine a base load and to then add other event blocks to the base load. The second method is to include the base load in each power block and then add the blocks in series. The first method was chosen for presentation of the FCCS consumables management concept because if offers flexibility in dealing with nominal and contingency situations. Figure 4.3-4 presents a graphical relationship between the electrical power block load profile and the predicted cryogen usage profile.

Cryogen Loading Data - Required loading quantities are provided as input data for use in the prelaunch analysis and evaluation sequence. Prior to loading cryogenic hydrogen and oxygen, the required loading values may be used for comparison with software calculations of total cryogen requirements.

Mission Constraint Data - Limit value data is used in the Constraint Module testing of actual consumables status data. Typical limit values are deltas between actual and predicted values, flow rate limits, and reserve limits.

B. Form of Input Data

Typical forms of input data are presented below:

Consumables Loading Requirements -

H_2 Tank	H_2 Quantity	O_2 Tank	O_2 Quantity
1	XXX	1	XXX
2	XXX	2	XXX

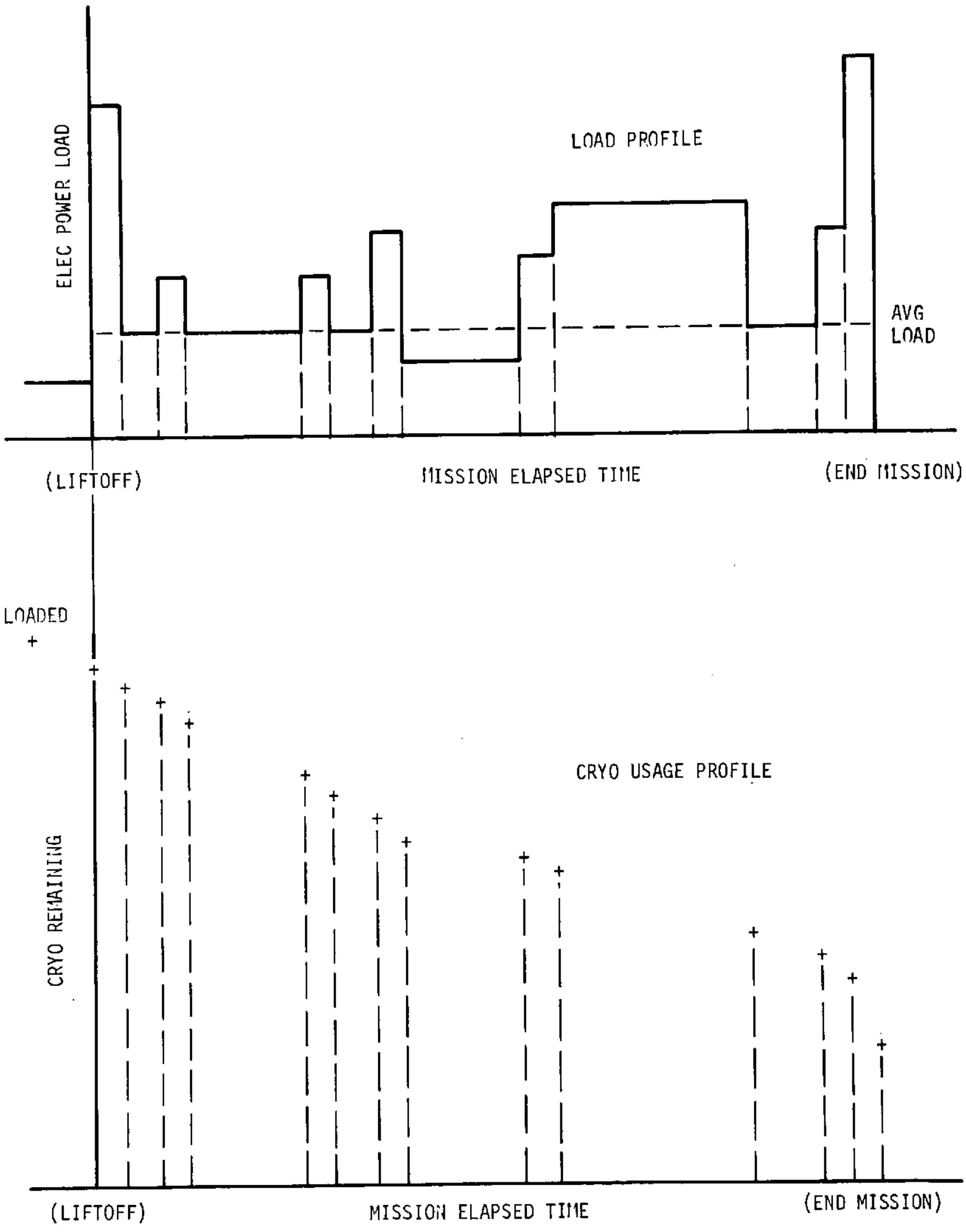


Figure 4.3-4. Relationship of Predicted Cryo Usage Profile to Electrical Power Load Profile

Constraints Data -

Parameter	Limit Value
ΔH_2	XX
ΔO_2	XX
H_2 Tank Balance	XX
O_2 Tank Balance	XX
H_2 EOMR	XX
O_2 EOMR	XX
H_2 Usage Rate	XX
O_2 Usage Rate	XX

Electrical Power Event Timeline -

Event Number	T Start (Hrs)	T End (Hrs)	Elec. Power Load	Event Type
1	0	116	8	Base Load-Nominal
2	-2	0	4	Prelaunch Load
3	0	0.5	14	Launch Load
4	1	1.5	5	Phasing
5	19	19.5	5	Height Adjustment
6	23	25	8	Rendezvous
7	25	47	-2	P/L Refurbishment
8	47	51	5	Orbit Adjustment
9	51	149	12	P/L Experiment
10	160	165	8	Deorbit Prep
11	165	168	16	Entry/Landing

4.3.4.2 FCCS Consumables Monitoring Data

The primary requirement for monitoring of the FCCS is the measurement of cryogen quantities per tank. Three measurement methods were investigated during the course of this study. They were pressure-volume-temperature (PVT), capacitance, and nucleonic techniques. Each measurement method considered is capable of zero-g operation and is compatible with the cryogens involved.

The first measurement method considered is a PVT type gauging system. This method has been proven on previous spacecraft programs and has been shown to be quite acceptable for bladder type pressurant storage systems such as the Apollo RCS. Previous Apollo experience[1] has shown that accurate quantity estimates involving cyrogenic H_2 are very difficult to obtain with any degree of regularity or certainty. Cryogenic O_2 measurements are more accurate than those of H_2 but the PVT approach is considered very limited in its application for consumables management. It could be used as an emergency backup, however.

The capacitance measurement of cryogen quantities was the primary technique used on the Apollo Service Module. This measurement technique will provide a fairly accurate (3 percent) measurement of quantity provided there exists a homogeneous mixture within the tank. In the case of the Apollo hydrogen tank, the quantity measurement was only valid when the mixing fans were on, or immediately after their turn-off, but before heater turn-on. The cryogenic oxygen measurements are also affected by stratification, but acceptable quantity measurements can be obtained when the cryogen is somewhat homogenous.

The third method investigated was a nuclear gauging technique. This technique measures cryogen quantities directly and is unaffected by stratification within the tank. Nucleonic gauging is the most accurate of the three methods with system accuracies better than 1%.

The features of the nuclear gauging make it the most attractive for consumables management purposes. However, capacitance probe measurements will be adequate if the externally mounted circulation pumps maintain homogeneous cryogen mixtures.

---

[1] Reference TRW Technical Report No. 17618-H234-RO-00, "Apollo 15 Mission CSM 112 Cryogenic Storage System Postflight Analysis Report", MSC/TRW Task E - 98A, November 1971.

An indirect alternate quantity measurement has also been considered, but is not shown on the FCCS flow diagrams. This alternate technique for the determination of cryogenic quantities is to integrate the total fuel cell current to obtain ampere-hours (AH). The AH's are directly proportional to cryogenic usage. The mechanization of this technique is quite simple. It would require the individual fuel cell currents to be monitored and integrated over some time interval. The ECLSS estimated cryogenic O_2 usage would be added to the calculated fuel cell usage to determine the total O_2 cryogenic usage. The major disadvantage of this technique is that it does not provide capability for leak detection, since there is no directly related cryogen measurement.

4.3.4.3 FCCS Crew Displays

A. Display Data

FCCS consumables management data required for crew display include constraint violation indications and consumables status data. A signal will be provided to activate a crew warning indication in the event a limit value violation is detected by the FCCS consumables management software.

Consumables status data displays which may be selected by the crew should include cryogen quantity and usage rate information, predicted end-of-mission quantities, and redline values.

B. Display Type

- Graphical Displays - FCCS consumables usage profiles and redlines should be available for display in graphical form in order to provide a quick assessment capability for the crew. Parameters presented on graphical displays should include predicted usage, actual usage, and redline values versus mission elapsed time for both cryogenic hydrogen and oxygen. A typical graphical display showing hydrogen quantities is presented in Figure 4.3-5. Values of total usage rate and predicted end-of-mission reserves may be included as shown on the graphical display for convenience in relating the graphical and tabular values.
- Tabular Displays - FCCS consumables data to be displayed in tabular form is shown by the typical display in Figure 4.3-6. This display demonstrates how subsystems parameters and consumables parameters may be grouped to form one convenient presentation of FCCS summary data.

```
                      TOTAL HYDROGEN REMAINING

P *
E * X                                   XXX PREDICTED
R * 0 X                                 000 ACTUAL
C *      X                              --- REDLINE
E *      0   X
N *             XO                          USAGE RATE   $.$$$
T *                X                    END PREDICTION   $$$.$
  * -                  X
R *   -                0    X    X
E *     -                       0    X
M *       -      -    -     -        0    X
  *                          -  -  -  -   -
  * * * * * * * * * * * * * * * * * * * * * * * * *
                          GROUND ELAPSED TIME
```

Figure 4.3-5.   Typical FCCS Graphical Display

$$$ HR $$ MIN $$ SEC

FUEL CELL/CRYOGENIC STATUS

FUEL CELLS	KW	VOLTS	AMPS	TEMP
FC 1	$$.$$	$$.$$	$$$.$	$$$.$
FC 2	$$.$$	$$.$$	$$$.$	$$$.$
FC 3	$$.$$	$$.$$	$$$.$	$$$.$

CRYOGEN	USE RATE	REMAINING	TOTAL EOM PRED
HYDROGEN TK 1	$.$$$	$$$.$$	$$$.$$
HYDROGEN TK 2	$.$$$	$$$.$$	
OXYGEN TK 1	$.$$$	$$$.$$	$$$.$$
OXYGEN TK 2	$.$$$	$$$.$$	

Figure 4.3-6. Typical FCCS Status Summary Format

4.3.5 FCCS Consumables Management Software Estimates

The FCCS consumables management software presented in Figures 4.3-1, -2, and -3 were used in preparing software sizing estimates. The estimates are summarized in Table 4.3-1 for each functional module.

A. Dynamic Data Storage Estimates

The ground supplied prelaunch data and the historical consumables status data are defined as dynamic data included in the storage estimates.

The storage estimates for the power event timeline were based on the assumption that fifty power blocks would be provided and that five data words would be used to describe each block. It was assumed that the intermediate output of the power profile could be adequately described by one hundred events. An additional one hundred words were allowed for cryogenic profile output data. Estimates for storage of H_2 and O_2 quantities were based on data samples at two-hour intervals throughout a seven-day mission. One thousand words are required to be available in scratch memory for inflight consumables predictions.

B. Fixed Data Storage Estimates

Estimates of fixed data storage requirements for the Prediction Module were prepared by comparing the Prediction Module with similar existing programs. The remaining module estimates were prepared by estimating the software required to perform the operations in the FCCS consumables management algorithms.

Table 4.3-1 FCCS Consumables Management Software Sizing Estimates

MODULE	FIXED STORAGE (words)	DYNAMIC STORAGE (words)
Evaluation	100	800
Constraint	200	-
Monitoring	75	-
Consumable Prediction	1500	250 Input Timeline 500 Power Profile 100 Output Data 1000 Words in Scratch Memory

4.4 MAIN PROPULSION SYSTEM/EXTERNAL TANKS (MPS/ET)

Main engine propellant is stored in external tanks and is supplied to the main engines during boost phase operation. Indications are that the external tanks will be filled for all missions and, under nominal conditions, a non-optimal trajectory will be flown to attain acceptable levels of residual propellant quantities prior to main engine cut-off.

4.4.1 MPS/ET Consumables Management Functions

MPS consumables are liquid hydrogen and liquid oxygen. The primary consumables management function applicable for MPS/ET operation is the monitoring of propellant quantities. Since the propellant monitoring is most useful if it can be easily related to other boost phase monitoring, the propellant quantity remaining should be displayed in terms of remaining delta-velocity (ΔV) capability. Remaining ΔV capability can easily be compared to G&N calculations of ΔV required to attain insertion conditions. The monitoring objective is to present information which can be used to ensure that remaining ΔV capability is always greater than ΔV to go. Constraint tests will provide indications which alert the crew to limit value violations.

4.4.2 MPS/ET Concept Selection Considerations

Main engine operation occurs during a short time interval which presents little opportunity to manage propellant usage. Boost phase monitoring of propellant usage is designed to supplement monitoring of the G&N parameters which are of primary importance. Therefore, the MPS/ET consumables management concept is to provide a very simple monitoring capability which provides information for correlation with G&N information.

4.4.3 MPS/ET Onboard Software Description

The MPS/ET consumables management software provides for monitoring and constraint testing of MPS/ET propellant usage during the prelaunch and boost phases of mission operation. Prelaunch ground supplied data includes an MPS event timeline, predicted fuel and oxidizer quantities required for launch, limit values, and predicted remaining ΔV versus mission elapsed time. The Monitoring Module calculates the remaining ΔV capability and velocity residual provided by the propellant quantities remaining. The remaining ΔV and velocity residual quantities are checked for limit value violations by tests performed by the Constraints Module.

The same consumables management software is employed for both the prelaunch and ascent phase monitoring activities.

Prelaunch Monitoring and Constraints Tests

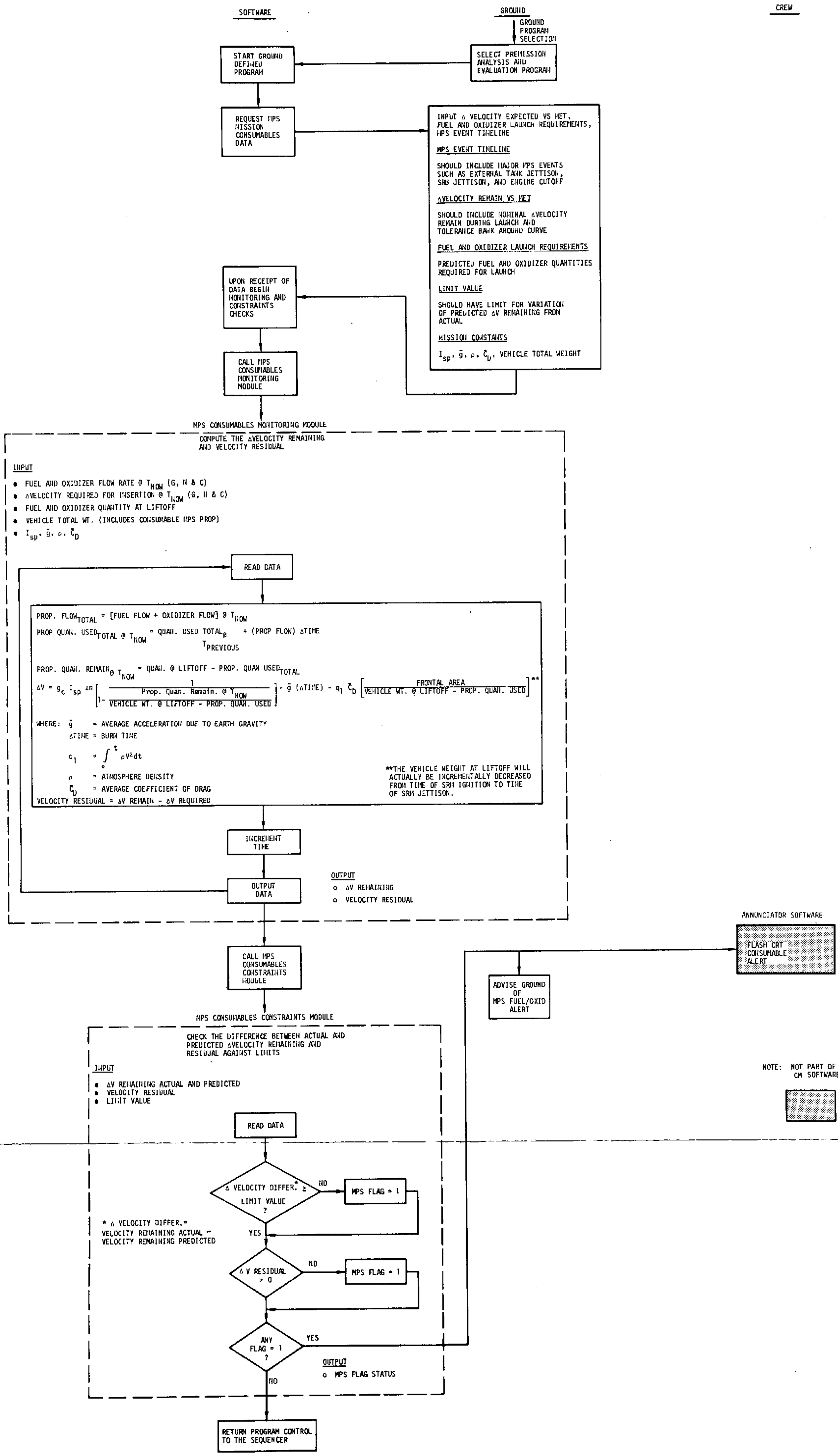
The functional software flow presented in Figure 4.4-1 describes the prelaunch consumables management software sequence of operations for performing monitoring and limit testing. The ground supplied data provided to the consumables management software includes an MPS event timeline which describes major events versus mission elapsed time including such events as solid rocket booster jettison, external tank jettison, and main engine cut-off times. In addition, the ground will supply a predicted remaining ΔV profile, total fuel and oxidizer quantities required at lift-off, and limit values for differences between predicted and actual remaining ΔV and for velocity residuals.

The Monitoring Module calculates the remaining ΔV capability and compares it with the G&N supplied value of ΔV required for insertion. The Monitoring Module calculations of remaining ΔV and velocity residuals are tested by the Constraints Module for limit value violations. A constraint violation will produce a signal to alert the ground that a limit test has failed and that corrective action is required.

Use of the MPS/ET consumables management software for prelaunch monitoring will serve to verify operation of the software and to verify adequacy of propellant quantities for launch.

Inflight Monitoring and Constraints Testing

The inflight sequence for the MPS/ET consumables management software is shown in Figure 4.4-2. The same software is used, and the same functions are performed, as was described for the prelaunch sequence.



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 4.4-1. MPS/ET Prelaunch Monitoring and Constraint Testing Sequence

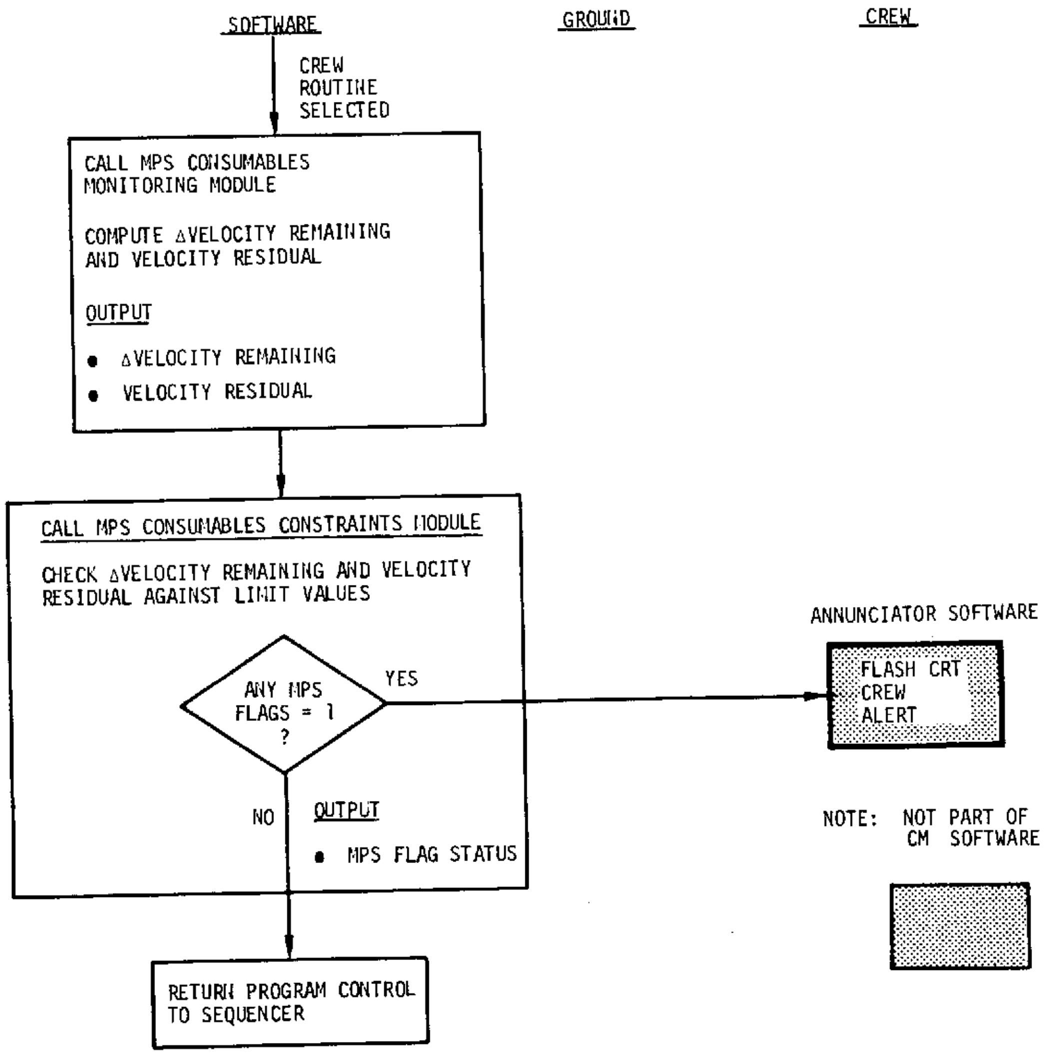


Figure 4.4-2. MPS/ET Inflight Monitoring and Constraints Testing Sequence

4.4.4 MPS/ET Input/Output Data Description

4.4.4.1 Mission Description Data

A. Input Data Required

The MPS/ET consumables management data described below is required for entry in the consumables management software prior to launch.

MPS Event Timeline - The major events related to MPS operation and their time of occurence will be required.

Remaining Delta Velocity Capability - A profile of the predicted remaining ΔV capability versus mission elapsed time is required. This data is used for comparison with inflight calculations of remaining ΔV.

Propellant Quantity Launch Requirements - Required quantities of fuel and oxidizer at launch must be provided.

Limit Values - Allowable limits must be provided for testing actual versus predicted remaining ΔV and for testing velocity residuals.

Mission Constants - Constants required include average acceleration due to earth gravity, average coefficient of drag, and atmospheric density. These are shown as single value constants in the flow charts, however, it may prove necessary to use curve fit data to provide better accuracy in the software calculations.

Main Engine Performance Data - Engine specific impulse data will be required for the main engines.

B. Form of Input Data

Typical forms of input data are described below.

MPS Event Timeline -

MET	Event
T_1	Launch
T_2	Staging
.	.
.	.
.	.
T_{MECO}	Main Engine Cut-off

Remaining ΔV Profile -

MET	Remaining ΔV
T_1	XXXX
T_2	XXXX
.	.
.	.
.	.
T_{MECO}	XXXX

Propellant Quantity Launch Requirements -

Propellant	Launch Quantity
H_2	XXXX
0_2	XXXX

4.4.4.2 MPS/ET Consumables Monitoring Data

The data required for MPS/ET software include flow rates and usable quantity at lift-off for both fuel and oxidizer. The fuel and oxidizer flow rates are required in G&N calculations and therefore, should be obtained from the G&N software.

Fuel and oxidizer quantities at lift-off will be determined by liquid level sensor measurements. If liquid level sensor signals are available onboard, the quantity data may be provided to the consumables management software. Otherwise, the quantity values must be provided by the ground prior to lift-off.

4.4.4.3 MPS/ET Crew Displays

The MPS/ET consumables management software provides two types of information for display to the crew. First, violations of limit values produce a signal to inform the crew that a constraint has been violated and that crew action is necessary.

Second, actual and predicted remaining ΔV capability values and velocity residual values will be available for display. The velocity residual values should be presented in digital form, but the remaining ΔV values may be displayed in graphical or tabular form. The displayed data will be most useful if it is grouped with related G&N parameters. Therefore, the choice of display form should be based on consideration of both G&N and MPS consumables data display requirements.

4.4.5 MPS/ET Consumables Management Software Estimates

Estimates of software sizing were prepared for the consumables management software shown in Figure 4.4-1. A summary of the estimates is presented in Table 4.4-1 which shows the estimates for both fixed and dynamic data storage for each module.

A. Dynamic Data Storage Estimates

Estimates of dynamic data storage requirements considers both ground supplied preflight data and inflight monitoring data storage. The estimates were prepared by assuming that ten major events would be included in the MPS event timeline and that the remaining ΔV profile would be adequately described by values at twenty time points. Storage was allowed for entering average acceleration due to gravity, average coefficient of drag, and average atmospheric density values at forty different time points.

B. Fixed Data Storage Estimates

Data storage requirements for the MPS/ET consumables management software fixed data were estimated by preparing sizing estimates of the software required for performing the MPS/ET consumables algorithms. Temporary storage of variables and instruction storage are included in the estimates shown.

Table 4.4-1. MPS/ET Consumables Management Software Sizing Estimates

MODULE	FIXED STORAGE (words)	DYNAMIC STORAGE (words)
Prediction	10	410
Monitoring	40	20
Constraints	15	10

4.5 REACTION CONTROL SYSTEM/ORBITAL MANEUVERING SYSTEM (RCS/OMS)

The concept proposed for management of RCS and OMS consumables usage combines management for the two subsystems into a single RCS/OMS consumables management system. This approach was chosen becuase of similarities in the consumables management requirements of the two subsystems. There is also commonality of input data requirements since operation of both subsystems is based on requirements for execution of burn programs. In the case of OMS operation, the RCS is used to supplement thrust vector control steering during an OMS burn.

The Orbital Maneuvering System consists of two reusable, pressure-fed rocket engines with propellant crossfeed capability. The propellant storage system will be provided in two pods. Each pod contains a high pressure helium storage bottle, tank pressurization regulators and controls, a fuel tank and an oxidizer tank.

The primary function of the OMS is to provide propulsive thrust to perform orbit circularization, orbit transfer, rendezous and de-orbit. The OMS is capable of burning all of its allocated propellant in either a single long burn or a series of multiple burns spread at random over the mission duration.

The Orbiter Reaction Control System consists of forty thrusters and six verniers separated into one forward and two aft modules. The RCS provides orbiter three-axis translation and vehicle attitude control capability during both the orbital and entry phases. During entry phase the RCS may be used to assist in orbiter attitude control. In addtition to its primary role, the RCS provides both a backup to the OMS and roll control steering for single engine OMS operation.

4.5.1 RCS/OMS Consumables Management Functions

The OMS consumables are nitrogen tetroxide (N_2O_4) as the oxidizer and monomethylhydrazine (MMH) as the fuel. A pod crossfeed line, employed in conjunction with individual engine isolation valves, allows all the propellant to be used by one engine in the event of an engine failure.

The consumable management function for the OMS is the determination of propellant reserves during the mission; this function results from the requirement to ensure deorbit delta-V capability. The OMS propellant usage may be controlled by the crew therefore, inflight prediction capability is necessary to effectively manage propellant usage and maintain adequate reserves.

The RCS consumable is a bipropellant combination of $N_2 O_4$ (oxidizer) and MMH (fuel). The propellant is stored in three non-interconnected systems which correspond to the three thruster modules. The propellant tanks are of the positive expulsion type with helium used as the pressurant. Presently, there is a separate helium pressurant source for the fuel tanks and oxidizer tanks for each system. This configuration will allow for separate determination of the individual fuel and oxidizer quantities for each thruster module.

The consumable management function for the RCS is two fold. First, functionally it must provide for propellant quantity monitoring, evaluation and prediction. Second, it must provide the computational software for inflight prediction and evaluation of RCS propellant for proposed revisions to the current mission plan. The crew may modify mission parameters to effect control of RCS propellant usage in order to accomplish nominal or contingency mission plans. Modification of mission parameters may consist of something as simple as deleting a single mission event or as complex as extensively revising a mission as required to accomplish specific objectives.

4.5.2 RCS/OMS Concept Selection Considerations

The proposed RCS/OMS consumables management concept provides monitoring evaluation, and prediction capability as well as inflight evaluation of mission revision effects on propellant usage. Selection of the proposed concept was influenced by consideration of criticality, controllability, and flexibility factors peculiar to RCS/OMS consumables management.

Both RCS and OMS propellants are critical to mission operation and are limited quantities which do not afford large reserves for many mission operations. Preliminary tank sizing/mission operations studies indicate that limitations on RCS and OMS propellant quantities preclude the luxury of management by excess. Therefore, active consumables management will be essential for effective utilization of RCS and OMS propellants to support mission operations.

Consumption of RCS and OMS propellants can be controlled to a great extent by active consumables management. In many cases there is considerable latitude in the choice of operational procedures which affect consumables usage. These options may be effectively employed to derive maximum benefit from each Shuttle mission by providing capability to support contingency operations and to pursue targets of opportunity.

Provision of adequate crew aids for actively managing RCS/OMS propellants reduces the necessity for continual ground support evaluation of proposed mission activities which impact consumables usage. Onboard capability is afforded by the proposed consumables management concept to predict consumables usage and end-of-mission reserves for both the nominal mission plan and revised mission plans. This will allow the crew to evaluate the capability of the RCS and OMS to support the mission and to take the necessary action to effectively utilize the propellants available.

Previous experience with Apollo and Skylab ground support systems has demonstrated the feasibility of the proposed technique for evaluating and predicting the impact of proposed mission changes on propellant usage. The RCS/OMS consumables management concept will use these proven techniques for calculating RCS/OMS consumables requirements onboard the vehicle.

4.5.3 RCS/OMS Onboard Software Description

The RCS/OMS consumables management software provides extensive capability for monitoring, evaluating, and replanning usage of RCS and OMS propellants. Data to be entered prior to launch includes an RCS/OMS major event timeline, burn schedule, attitude timeline, propellant loading requirements, mass properties data, and constraints data values. After the input data is processed, the RCS/OMS consumables management software provides propellant usage profiles, predicted end-of-mission reserve values for RCS and OMS propellants, and tests for limit value violations. Inflight operation provides for monitoring the status of propellant quantities and evaluating the quantity values as compared to predicted and limit values. Inflight replanning of consumables usage is provided by entering the necessary mission revision data after which the consumables management software will provide revised RCS usage profiles and propellant end-of-mission reserve data.

Prelaunch Analysis and Evaluation

Functional software flow for the RCS/OMS consumables management software prelaunch operations is shown in Figure 4.5-1. The consumables Prediction Module, Evaluation Module, and Constraints Module are utilized in the prelaunch sequence of operations. If propellant loading has been completed, the Monitoring Module will also be employed in providing actual propellant loading data.

Ground supplied data which is required by the RCS/OMS consumables management software includes the following:

- o Major event timeline - indicates the mission elapsed time at which events are scheduled.
- o Burn schedule - denotes the propulsion system to be used, velocity to be gained, and mission elapsed time of scheduled burns.
- o Attitude timeline - indicates mission elapsed time for maneuvers and attitude hold periods. Denotes attitude hold deadbands and maneuver rates.
- o Propellant loads - indicates required loading values for RCS and OMS tanks.
- o Mass properties - provides vehicle mass properties and mission elapsed time schedule of payload events affecting mass properties.
- o Mission consumables constraint data - provides values for redline data, end-of-mission reserve limits, tank balance limits, and limit deltas between actual and predicted quantity values.

After the input data has been supplied by the ground system, the Consumables Prediction Module is called to calculate RCS and OMS propellant usage for the scheduled mission events. The event usage provides data for generating predicted propellant usage profiles and total propellant usage for the complete mission. The Evaluation Module is called to calculate predicted end-of-mission reserve values for both RCS and OMS propellants.

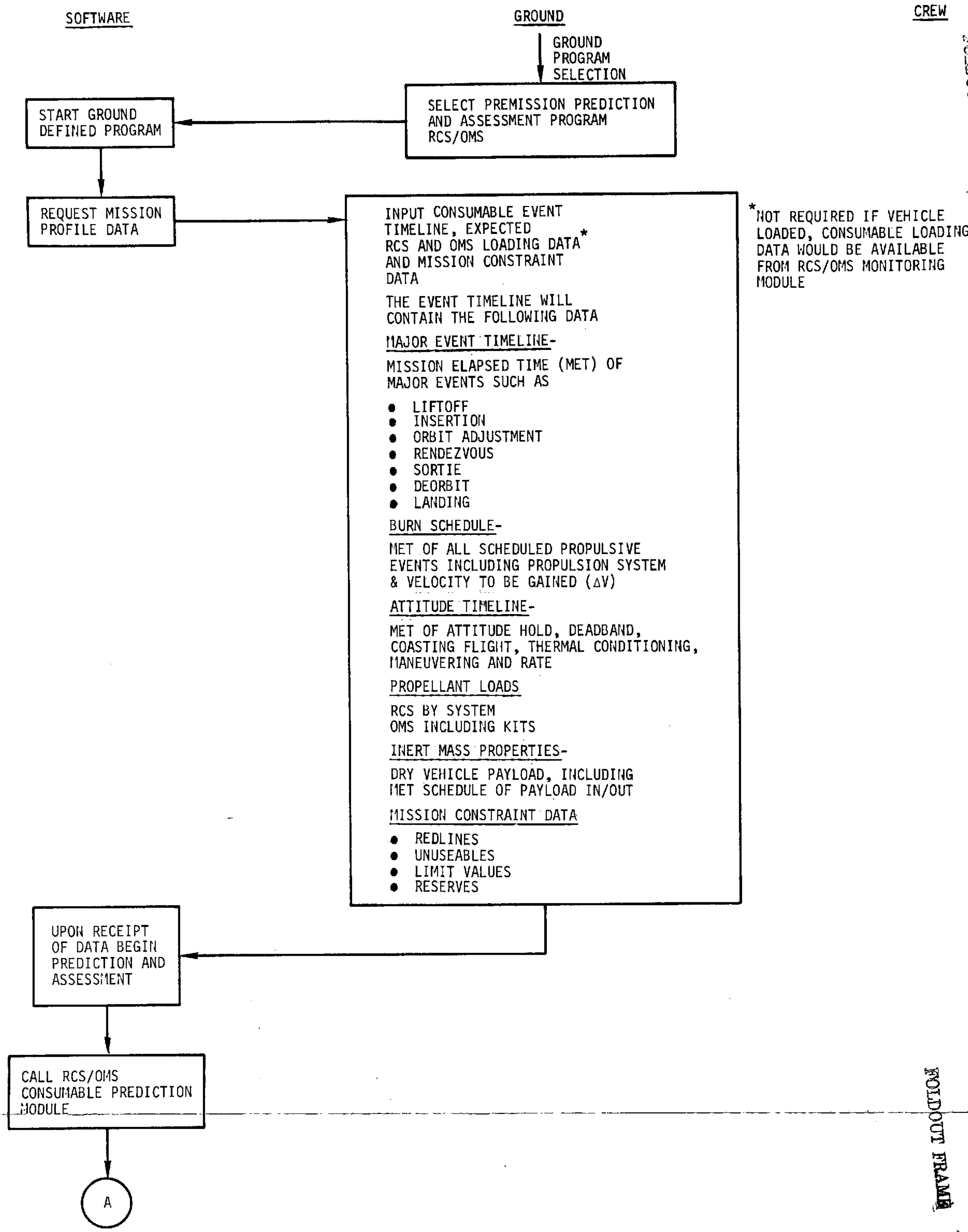
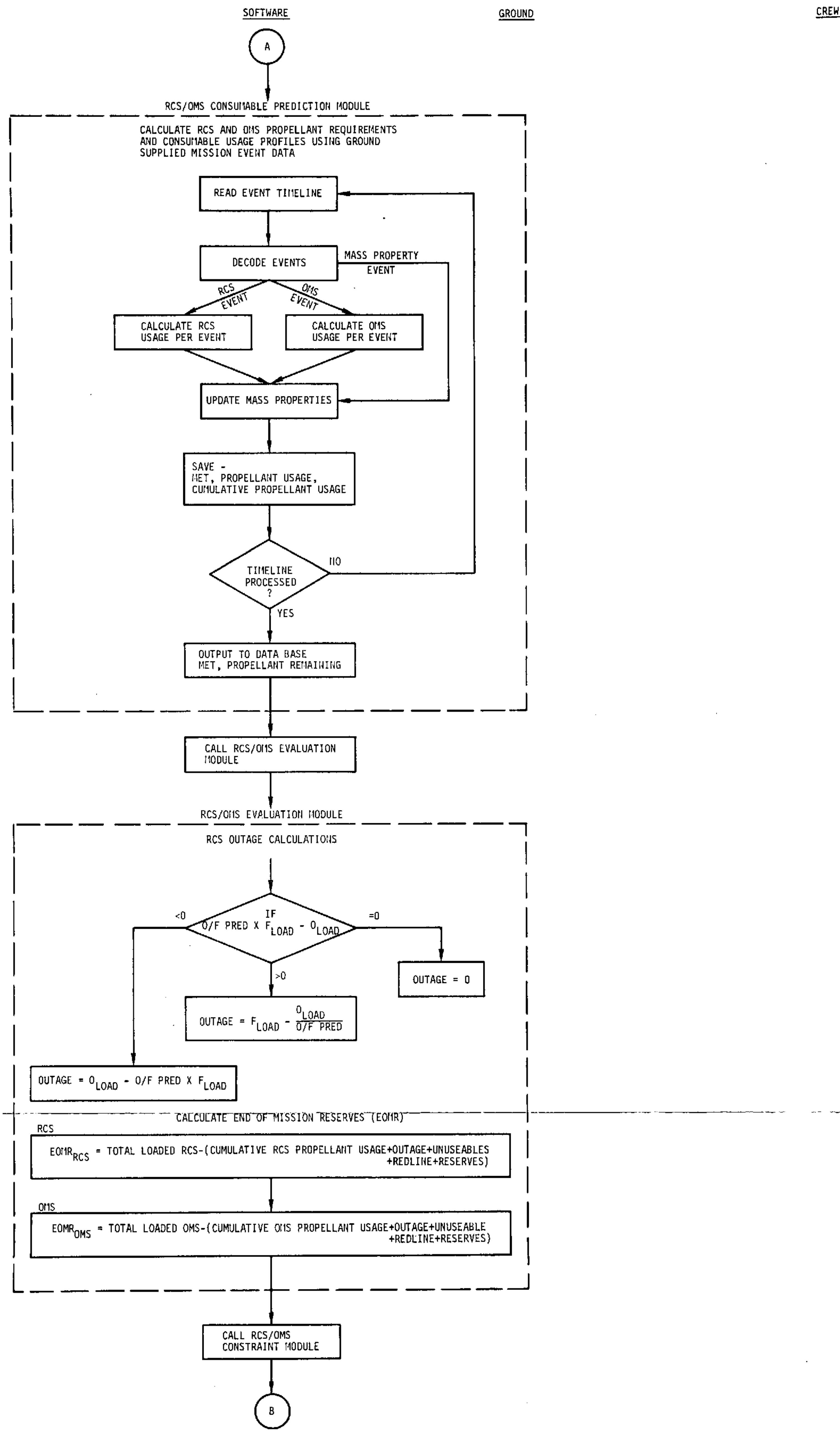


Figure 4.5-1. RCS/OMS Prelaunch Analysis and Evaluation Sequence.



FOLDOUT FRAME

FOLDOUT FRAME 2

Figure 4.5-1. RCS/OMS Prelaunch Analysis and Evaluation Sequence (Continued).

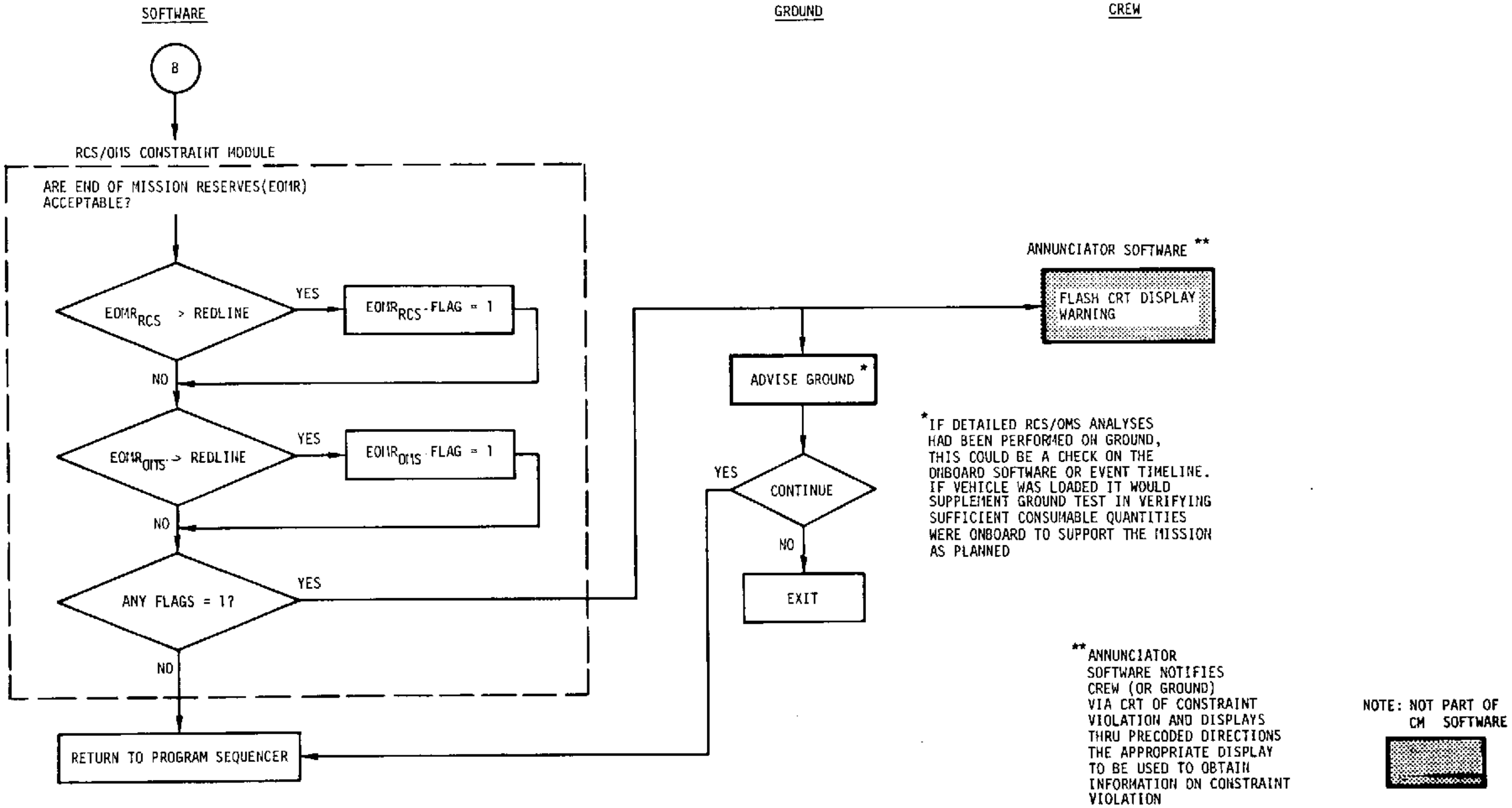


Figure 4.5-1. RCS/OMS Prelaunch Analysis and Evaluation Sequence (Concluded).

The RCS and OMS end-of-mission reserves are calculated by differencing the predicted RCS and OMS propellant requirements from the amount available for mission planning. The amount available for mission planning is determined by subtracting the unuseable, redline and propellant outage quantities from the total loaded. Defining end-of-mission reserves differently will not alter the functional requirements of the RCS/OMS Evaluation Module.

The last module called in the sequence is the RCS/OMS Constraint Module. The RCS/OMS Constraint Module shall provide the capability to determine out of tolerance conditions regarding the RCS and OMS consumable status and to issue a ground alert signal. For the premission sequence, the only applicable constraint check is on the end-of-mission reserves. Most likely such a check would involve use of the RCS and OMS redline values which have been input from the ground system.

Detection of a constraint violation would indicate that action is required by the ground support system to determine the source of the violation. Possible causes of a violation include inadequate quantities of propellant loaded, an error in the ground supplied mission data, and an error in the onboard software. Thus, successful performance of the prelaunch sequence will provide verification of the software operation and propellant loading.

Inflight Monitoring and Evaluation Sequence

The functional software flow for the inflight monitoring and evaluation is shown in Figure 4.5-2. The Monitoring Module, Evaluation Module, and Constraints Module are utilized in performing the monitoring and evaluation of consumables status.

The Monitoring Module utilizes subsystem sensor data for determining propellant quantities remaining in each storage system. Calculations are performed to provide values of RCS and OMS total propellant quantity remaining as well as providing RCS tank balance values.

SOFTWARE | GROUND | CREW

COMPUTER ROUTINE SELECTION

CONSUMABLE MONITORING AND EVALUATION

CALL RCS/OMS MONITORING MODULE

UPDATE DATA BASE WITH MEASURED OR CALCULATED PROPELLANT QUANTITIES

RCS QUANTITY REMAINING CALCULATIONS (PVT TECHNIQUE)

$$\begin{bmatrix} \text{RCS SYS 1 REMAINING}_{PVT}\ \text{OX} \\ \text{RCS SYS 1 REMAINING}_{PVT}\ \text{FU} \\ \text{RCS SYS 2 REMAINING}_{PVT}\ \text{OX} \\ \text{RCS SYS 2 REMAINING}_{PVT}\ \text{FU} \\ \text{RCS SYS 3 REMAINING}_{PVT}\ \text{OX} \\ \text{RCS SYS 3 REMAINING}_{PVT}\ \text{FU} \end{bmatrix} = \begin{bmatrix} \text{WEIGHTING} \\ \text{MATRIX} \end{bmatrix} \begin{bmatrix} \text{PRESSURE} \\ \text{TEMPERATURE} \end{bmatrix}$$

WEIGHTED AVERAGING

RCS SYS 1 REMAINING OX = A_1X RCS SYS 1 REMAINING $_{PVT}$ OX + B_1 X RCS SYS 1 REMAINING$_{DIRECT}$ OX

RCS SYS 1 REMAINING FU = A_2X RCS SYS 1 REMAINING $_{PVT}$ FU + B_2 X RCS SYS 1 REMAINING$_{DIRECT}$ FU

RCS SYS 2 REMAINING OX = A_3X RCS SYS 2 REMAINING $_{PVT}$ OX + B_3 X RCS SYS 2 REMAINING$_{DIRECT}$ OX

RCS SYS 2 REMAINING FU = A_4X RCS SYS 2 REMAINING $_{PVT}$ FU + B_4 X RCS SYS 2 REMAINING$_{DIRECT}$ FU

RCS SYS 3 REMAINING OX = A_5X RCS SYS 3 REMAINING $_{PVT}$ OX + B_5 X RCS SYS 3 REMAINING$_{DIRECT}$ OX

RCS SYS 3 REMAINING FU = A_6X RCS SYS 3 REMAINING $_{PVT}$ FU + B_6 X RCS SYS 3 REMAINING$_{DIRECT}$ FU

[INITIALIZE WITH $A_1 \rightarrow A_6$ & $B_1 \rightarrow B_6$ = 0.5]

TOTAL RCS REMAINING$_{FWD}$ = RCS SYS1 REMAINING OX + RCS SYS 1 REMAINING FU

TOTAL RCS REMAINING$_{AFT}$ = RCS SYS2 REMAINING OX + RCS SYS2 REMAINING FU + RCS SYS3 REMAINING FU + RCS SYS 3 REMAINING OX

TOTAL RCS USED$_{FWD}$ =TOTAL RCS LOADED$_{FWD}$ - TOTAL RCS REMAINING$_{FWD}$

TOTAL RCS USED$_{AFT}$ = TOTAL RCS LOADED$_{AFT}$ - TOTAL RCS REMAINING$_{AFT}$

RCS TANK BALANCE CALCULATION

RCS TANK BALANCE$_{AFT}$ = |RCS SYS2 REMAINING OX + RCS SYS2 REMAINING FU - (RCS SYS3 REMAINING OX + RCS SYS3 REMAINING FU)|

OMS BACKUP QTY REMAINING CALCULATIONS

OMS SYS1 REMAINING = OMS SYS1 REMAINING-ENG 1 ON TIME X ENG 1 FLOW RATE

OMS SYS2 REMAINING = OMS SYS2 REMAINING-ENG 2 ON TIME X ENG 2 FLOW RATE

[INITIALIZE WITH OMS SYS1 AND OMS SYS2 REMAINING = OMS PROPELLANT LOADED PER SYSTEM]

TOTAL OMS REMAINING = OMS SYS1 REMAINING + OMS SYS2 REMAINING

CALL RCS/OMS EVALUATION MODULE

RCS/OMS EVALUATION MODULE

CALCULATE DELTA'S BETWEEN ACTUAL AND PREDICTED QUANTITIES AND END OF MISSION RESERVES (EOMR) AT MET$_{NOW}$

RCS

DELTA RCS$_{FWD}$ = RCS SYS 1 REMAINING - RCS SYS 1 PREDICTION

DELTA RCS$_{AFT}$ = RCS SYS 2 REMAINING + RCS SYS 3 REMAINING - RCS$_{AFT}$ PREDICTION

OUTAGE CALCULATIONS

INFLIGHT OUTAGE$_{AFT}$ = TOTAL AFT RCS REMAINING - TOTAL AFT RCS USEABLE + $\dfrac{\text{1 + O/F PRED X AFT RCS PRED}}{1 + \dfrac{\text{RCS OX USED}}{\text{RCS FU USED}}}$

DELTA OUTAGE = | PREFLIGHT OUTAGE - INFLIGHT OUTAGE |

EOMR$_{RCS}$ FWD = EOMR$_{RCS}$ PREFLIGHT + DELTA RCS$_{FWD}$

EOMR$_{RCS}$ AFT = EOMR$_{RCS}$ PREFLIGHT + DELTA RCS$_{AFT}$ - DELTA OUTAGE

OMS

DELTA OMS = TOTAL OMS REMAINING - OMS PREDICTION

OMS ΔV CAPABILITY = g ISP$_{OMS}$ ln $\dfrac{W_V}{W_V\text{-TOTAL OMS REMAINING}}$

EOMR$_{OMS}$ = EOMR$_{OMS}$ PREFLIGHT + DELTA OMS

OMS ΔV EOMR = g ISP$_{OMS}$ ln $\dfrac{W_V}{W_V\text{-EOMR}_{OMS}}$

A

Figure 4.5-2. RCS/OMS Inflight Monitoring and Evaluation Sequence.

FOLDOUT FRAME

FOLDOUT FRAME 2

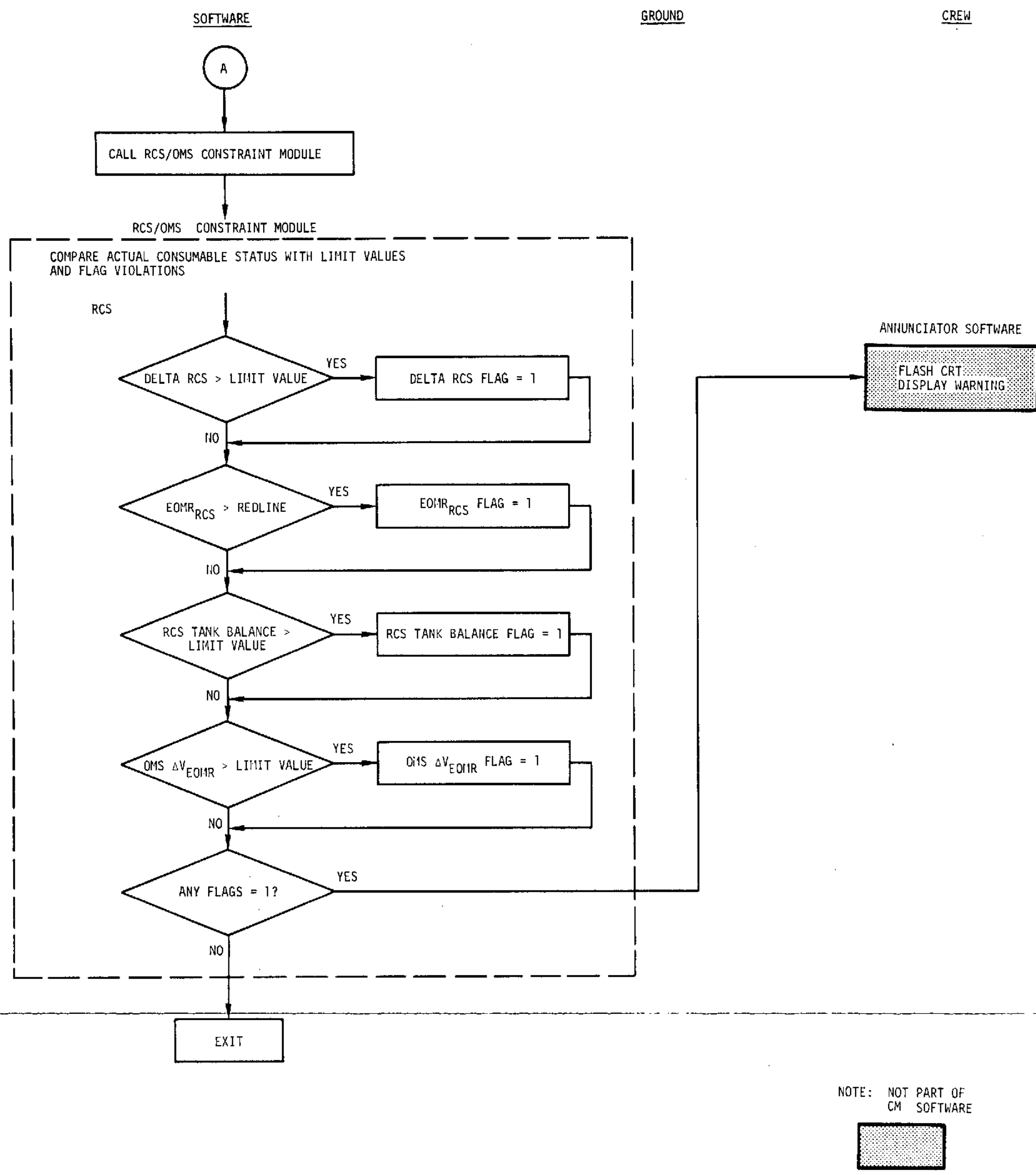


Figure 4.5-2. RCS/OMS Inflight Monitoring and Evaluation Sequence (Concluded).

FOLDOUT FRAME

FOLDOUT FRAME

Evaluation Module calculations include updated end-of-mission reserve values for both RCS and OMS propellants, OMS remaining ΔV capability, and comparison of actual versus predicted propellant quantities.

The Constraints Module is used to compare RCS and OMS consumables status with the mission consumables constraint data. Inflight comparisons are performed for RCS tank balance, end-of-mission reserves, and predicted versus actual quantity remaining. End-of-mission reserves are predicted values therefore, a constraint violation of reserve values would be a warning that a problem is predicted to occur later in the mission. Other types of violations are indicative of an existing problem which requires corrective action. The constraint violations will provide a signal to warn the crew of a problem.

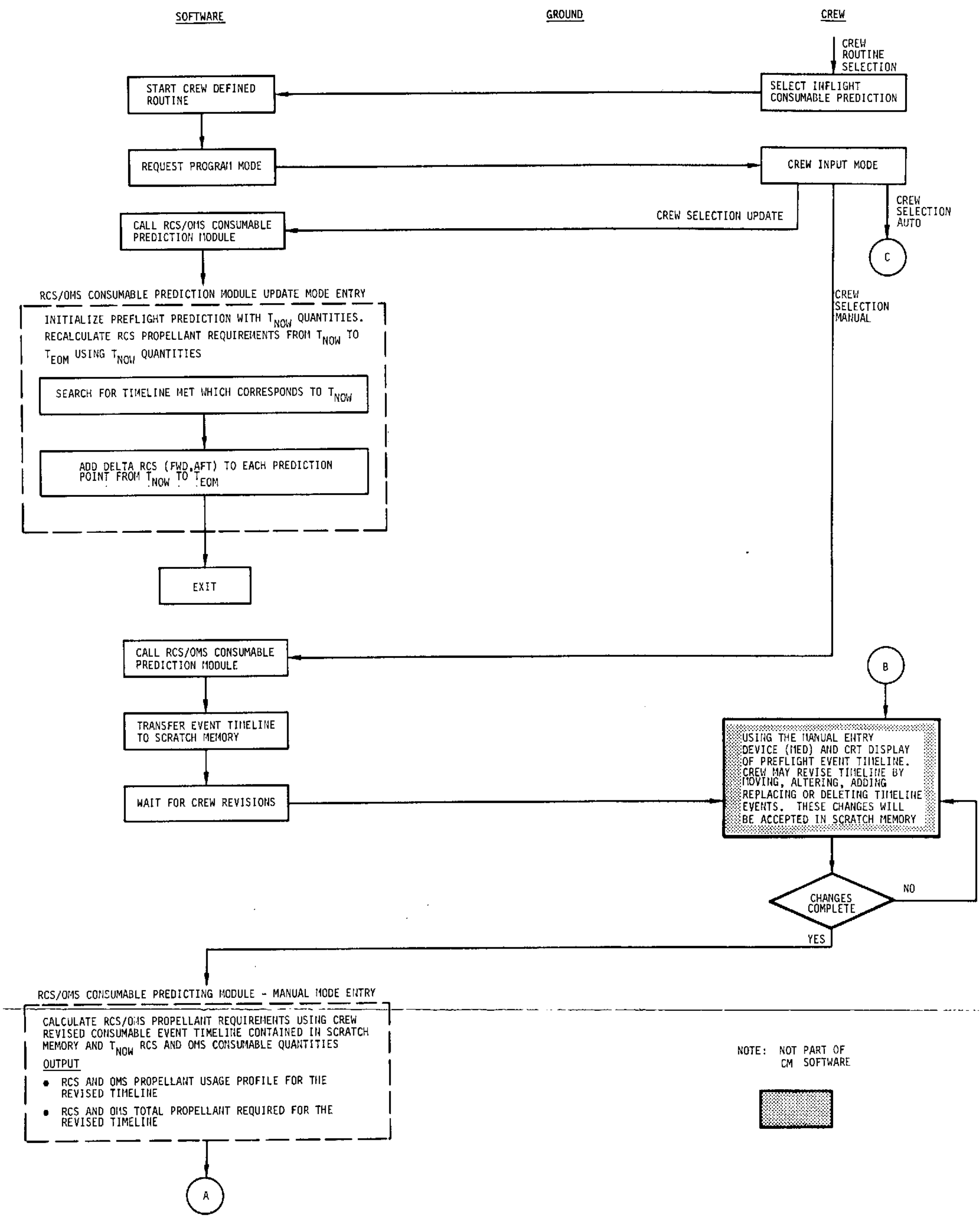
Inflight Consumables Prediction Sequence

The RCS/OMS consumables prediction sequence functional software flow is shown in Figure 4.5-3. The Prediction Module, Evaluation Module, Monitoring Module, and Constraints Module are all utilized in this sequence of operation.

There are three optional methods of utilizing the inflight prediction sequences. The prediction update entry, manual entry consumables prediction, and automatic entry consumables prediction modes may be selected by the crew.

The prediction update feature is designed to initialize the existing predicted usage profiles so that predicted and actual quantities are equal at the update time, T_{NOW}. There is no revision of mission events involved in the update therefore, the predicted usage profile retains the same form and the entire profile only is shifted as required for reinitialization. The requirement for this capability arises when past mission activities have resulted in deviation of the actual usage profile from the predicted profile. Reinitializing the predicted usage profiles makes it easier for the crew to interpret the significance of the displayed information with regard to the remainder of the mission.

FOLDOUT FRAME



FOLDOUT FRAME 2

Figure 4.5-3. RCS/OMS Inflight Consumables Prediction Sequence.

FOLDOUT FRAME

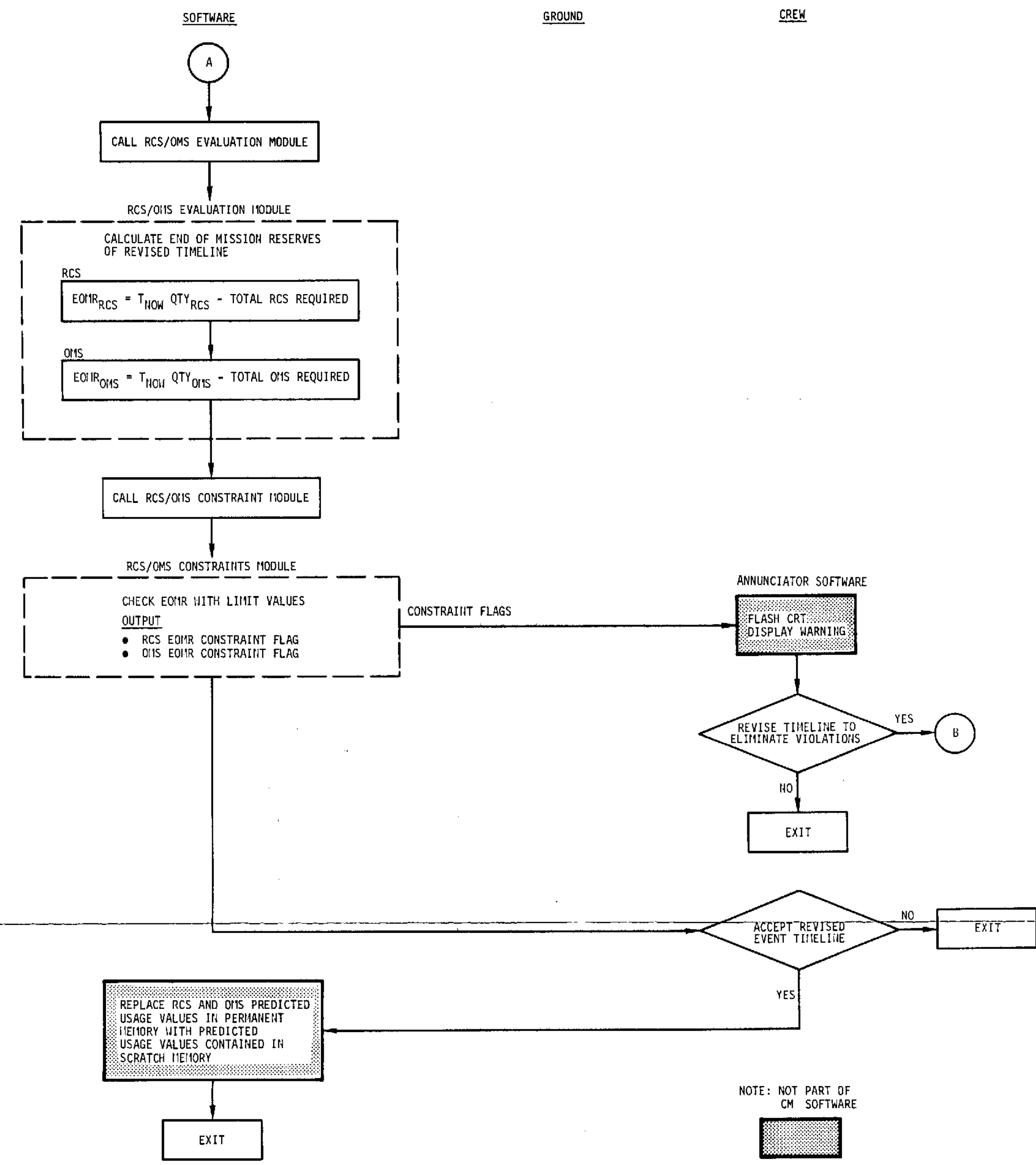


Figure 4.5-3. RCS/OMS Inflight Consumables Prediction Sequence (Continued)

FOLDOUT FRAME 2

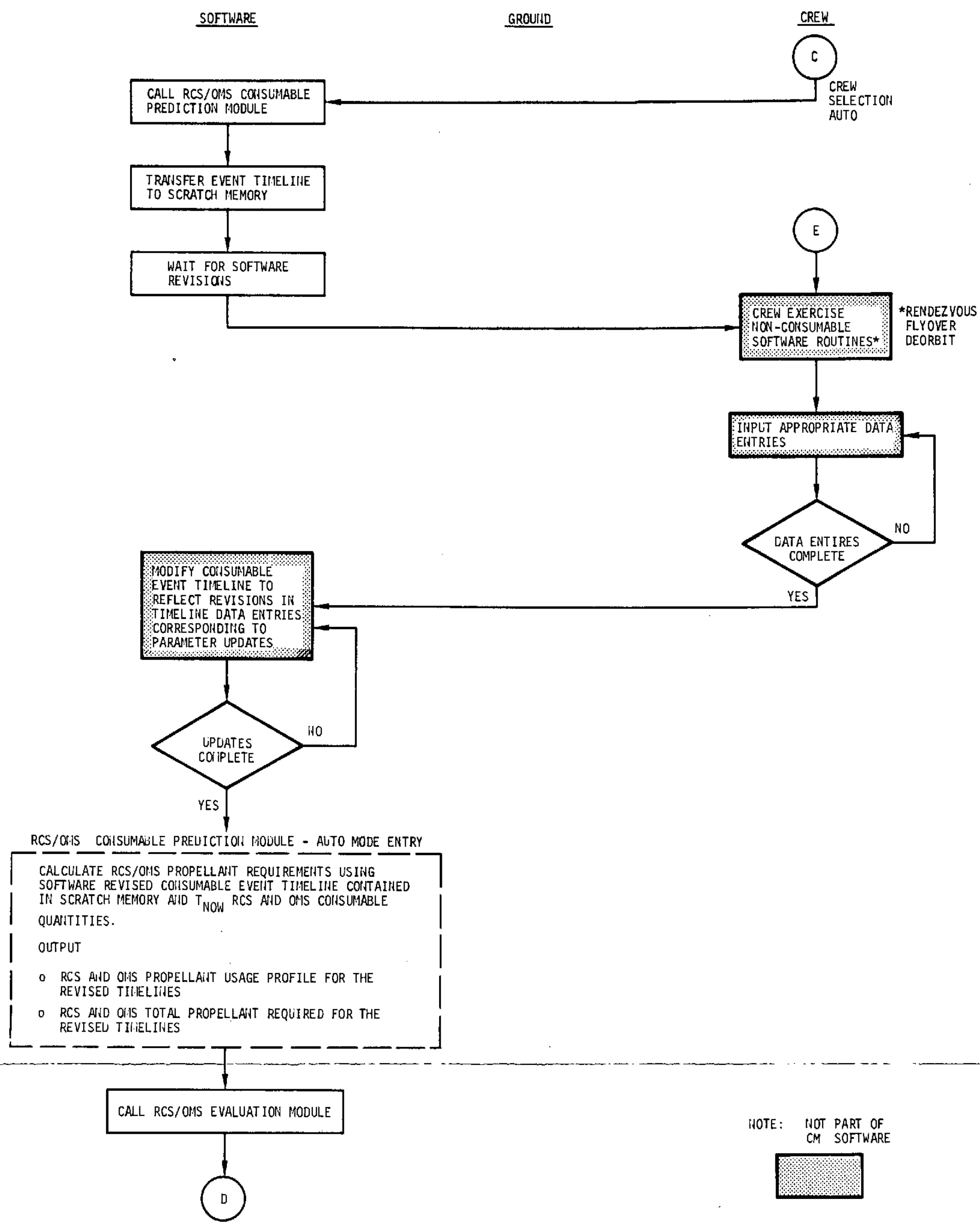


Figure 4.5-3. RCS/OMS Inflight Consumables Prediction Sequence (Continued)

FOLDOUT FRAME 1
FOLDOUT FRAME 2

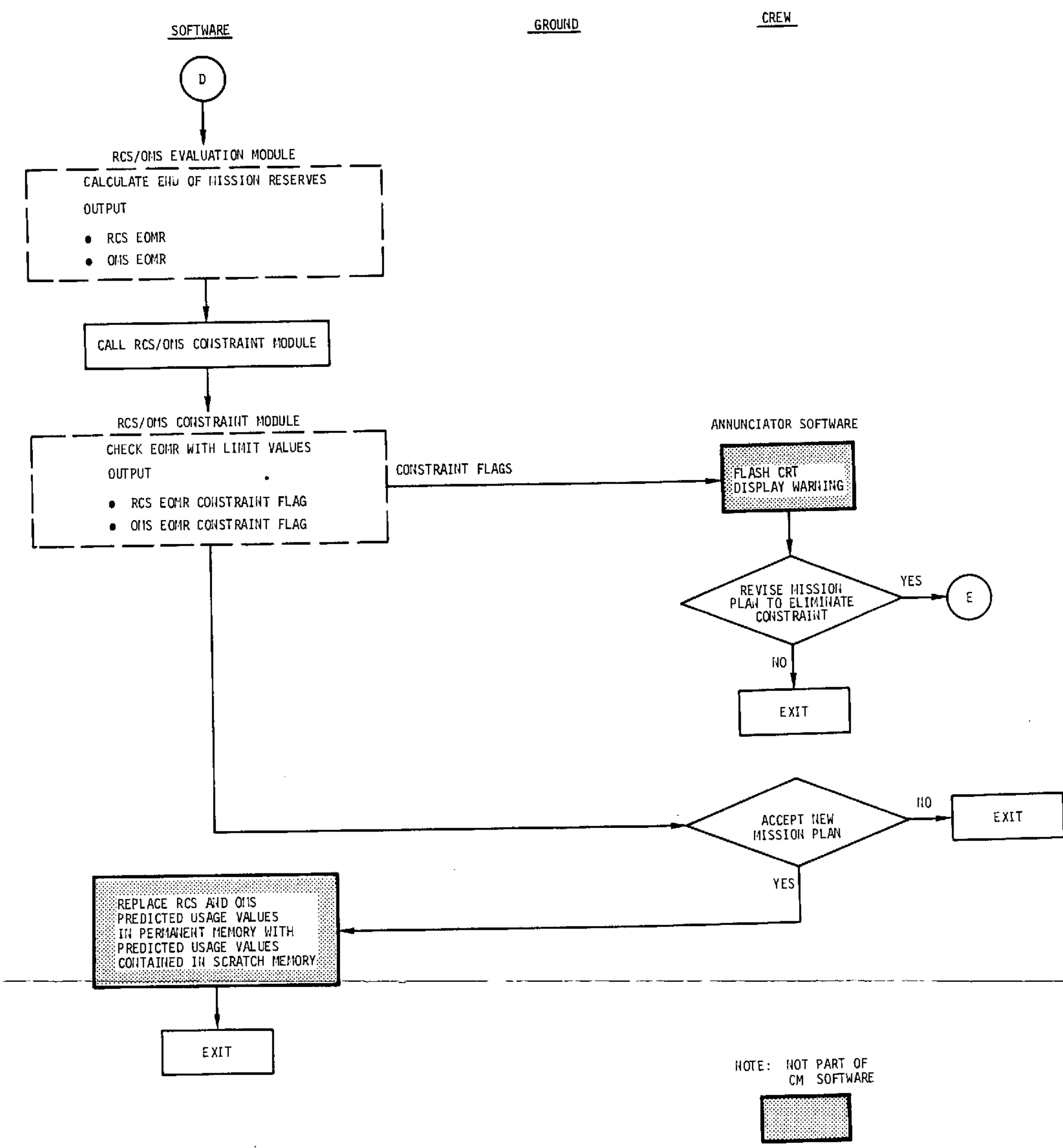


Figure 4.5-3. RCS/OMS Inflight Consumables Prediction Sequence (Concluded)

FOLDOUT FRAME
FOLDOUT FRAME 2

The consumables usage predictions may be revised by either manual or automatic entry of mission revisions. The crew may perform revisions by manually entering data to revise the existing timeline by adding, deleting, or rescheduling timeline events. The revised timeline is processed in the Prediction Module to obtain new RCS and OMS propellant usage profiles after which the Evaluation Module calculates revised values of end-of-mission reserve quantities. The Constraints Module is used to check the revised end-of-mission reserve values for limit value violations. If no violations are detected, the crew may choose to accept the revised timeline data for entry in permanent storage and subsequently the consumables management calculations will use the revised information for all comparisons and tests.

The inflight consumables prediction capability allows the crew to utilize the consumables available to obtain maximum benefit from the mission.

The automatic entry feature may be employed to enter revised timeline data obtained from certain non-consumables management software routines. Typical routines which can supply such revision data include rendezvous programs, deorbit programs, and other related G&N programs whose outputs provide data defining velocity to be gained and time of ignition. The automatic entry feature would allow the crew to immediately assess the impact of proposed revisions on RCS and OMS propellant quantities and end-of-mission reserves. After the revised timeline data is entered, the consumables prediction, evaluation, and constraints test sequence is the same as was described for the manual entry prediction sequence.

4.5.4 RCS/OMS Input/Output Data Description

4.5.4.1 Mission Description Data

A. Input Data Required

For the RCS/OMS consumables management software shown in Figures 4.5-1, -2, and -3, the data which follow are required to be entered prior to launch.

Major Event Timeline - An event timeline is required which lists the time sequence of events such as liftoff, insertion, rendezvous, deorbit, and landing.

RCS/OMS Burn Schedule - A schedule of translation maneuvers is required including the propulsion system to be used and the velocity to be gained for each maneuver.

Attitude Timeline - Attitude information required includes event versus mission elapsed time descriptions of attitude information such as attitude hold and deadbands, maneuvers and maneuver rates, coasting flight, and thermal conditioning periods.

Propellant Loading Data - RCS and OMS propellant loading requirements are to be provided for all storage systems including add-on kits.

Mass Properties Data - Mass Properties data are required including dry vehicle and payload mass properties data versus mission elapsed time.

Constraints Data - Values are required for constraints data including reserves, redlines, and deltas between predicted and actual values.

B. Form of Input Data

Typical forms for providing input data are described below.

Major Event Timeline -

MET	Event
T_1	Liftoff
T_2	Orbit Insertion
.	.
.	.
.	.
T_f	Enter Atmospheric Flight Regime

Burn Schedule -

MET	ΔV	Propulsion System
T_1	XX	RCS +X
T_2	XXX	OMS
.	.	.
.	.	.
.	.	.
T_f	XXX	OMS Deorbit

Attitude Timeline -

MET Start	MET Stop	Event Description
T_1	T_2	Attitude Hold, Wide deadband
T_3	T_4	20 deg Roll, 0.05 deg/sec
T_{f1}	T_{f2}	Entry Attitude Hold, Wide Deadband

Propellant Loading Data -

OMS System	Quantity N_2O_4	Quantity MMH
1	XXX	XXX
2	XXX	XXX

RCS System	Quantity N_2O_4	Quantity MMH
1	XXX	XXX
2	XXX	XXX
3	XXX	XXX

4.5.4.2 RCS/OMS Consumables Monitoring Data

A. Parameters Required

The RCS and OMS parameters required for consumables management are values of propellant quantities for each tank. Both nitrogen tetroxide and monomethylhydrazine quantities must be provided.

B. Measurement Method

For the RCS, two types of measurement techniques were investigated. They consisted of a pressure-volume-temperature technique (PVT) and a direct reading gas density measurement technique (ρV). The nucleonic method was not considered because of the weight penalty involved in using this system on the numerous RCS propellant tanks.

The PVT method has been employed to measure RCS quantities on the Apollo system. Two PVT techniques were used to help reduce the temperature stabilization problem associated with the periods of high propellant usage. During periods of high propellant usage the pressurant temperature would rise thus causing the corresponding propellant quantity indication to drop below the quantity actually present. As the system temperatures stabilized, it appeared that propellant was being added back into the tank. To help minimize this effect, additional temperature measurements were employed and a weighting was applied to the pressure temperature measurements for the Apollo ground support system calculations.

The gas density measurement technique (ρV) measures the ullage density directly rather than estimating it as the PVT approach does. This measurement technique is more accurate than the standard PVT technique and provides accurate quantity estimates at all times, including periods of high propellant usage. The amount of instrumentation required for the ρV technique is essentially the same as the standard PVT technique. For the consumable management concept, the ρV measurement method is attractive because it is capable of attaining higher accuracies and is less affected by temperature variations than the standard PVT technique.

For the OMS, three types of measurement methods were considered. They were liquid level sensors, pressure volume temperature (PVT) and nucleonic. Only the PVT and nucleonic gauge can be used for zero-g measurements. The liquid level sensor approach is the simplest of the three approaches considered and is relatively accurate, but it can only be used when the propellant is properly positioned in the tank.

The PVT method is the least accurate of the three methods considered, but it can be used for zero-g measurements. Because the OMS is not a bladder type storage system, additional compensation for the PVT technique will have to be added to account for pressurant absorption by the propellants. This technique, as stated in the RCS PVT discussion, is also subject to erroneous indication due to temperature variations throughout the system during periods of high usage.

The nuclear gauging method is a promising technique investigated for OMS propellant gauging because it is very accurate and provides measurements under zero-g conditions. Nuclear gauges mounted external to the OMS tanks provide direct measurement of propellant mass independent of obstructions or baffles within the tanks.

4.5.4.3 RCS/OMS Crew Displays

A. Display Data

Crew display information for RCS/OMS consumables management include constraint violation indications and propellant status data. Limit value violations detected by the Constraints Module tests will produce a signal to warn the crew of the violation.

Consumables status data which is required to be available for display to the crew include both fuel and oxidizer quantity information for the RCS and OMS. OMS data will include tank quantities of fuel and oxidizer and the remaining ΔV capability. RCS data will include fuel and oxidizer tank quantities; predicted end-of-mission reserves; and profiles of predicted, actual, and redline values.

B. Display Types

A system such as the OMS which uses consumables in discrete quantities does not typically require a separate consumables display. Rather, the OMS consumables parameters can be used more effectively when combined with related OMS systems performance parameters in a single display. Figure 4.5-4 shows a typical display format in which both OMS propellant data and subsystems status data are summarized.

Displays are required for total RCS propellant usage profiles including predicted, actual, and redline quantities versus mission elapsed time. Graphical displays provide a visual display of differences between predicted, redline, and actual quantities. In addition, the graphical format permits the crew to see the trend of actual propellant usage. A typical graphical format for RCS consumables is shown in Figure 4.5-5.

Tank quantity information can be effectively combined with RCS subsystem data for display. One useful form of display is the schematic, or stick-chart, format, as shown in Figure 4.5-6, which shows subsystem configuration status and tank quantities on a common display.

4.5.5 RCS/OMS Consumables Management Software Estimates

Software sizing estimates were prepared for the RCS/OMS consumables management software shown in Figures 4.5-1, -2, and -3. A summary of the estimates is presented in Table 4.5-1.

A. Dynamic Data Storage Estimates

The data included in dynamic data estimates are the ground supplied premission data and the consumables status data acquired during flight. Estimates of consumables status data storage were based on assuming a seven day mission and storing propellant status data at two hour intervals. One hundred events were allowed for the input event timeline. An additional one thousand words are required to be available in scratch memory for inflight consumables predictions.

$$$ HR $$ MIN $$ SEC

OMS STATUS

ENGINE	CHAMBER PRESS	FUEL TEMP	OX TEMP	
NO. 1	$$$.$	$$$.$	$$$.$	
NO. 2	$$$.$	$$$.$	$$$.$	
PRESSURANT	TANK PRESS	TANK TEMP	FUEL PRESS	OXID PRESS
HE TK 1	$$$.$	$$$.$	$$$.$	$$$.$
HE TK 2	$$$.$	$$$.$	$$$.$	$$$.$
PROPELLANT	FUEL REM	OX REM	ΔV REM	
FUEL TK 1	$$.$	$$.$	$$$.$	
FUEL TK 2	$$.$	$$.$		
OX TK 1	$$.$	$$.$		
OX TK 2	$$.$	$$.$		

Figure 4.5-4. Typical OMS Summary Format

```
$$$ HR  $$ MIN  $$ SEC
                   TOTAL RCS PROPELLANT REMAINING
      P *XOX  X
      E *     XO                              XXX PREDICTED
      R *       XOX X  X                      000 ACTUAL
      C *           0  XO                     ... REDLINE
      E *              X X 0 X X 0 X
      N *                          OX X X
      T *                            0   X    EOM PRED $$$.$
        *                              0  X
      R *                               0  X X X  X X
      E *......                            0  0      X
      M *      ....... . . .                      0
        *                  . .. . .. . ... . ...
        * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                    GROUND ELAPSED TIME
```

Figure 4.5-5.   Typical RCS Graphical Display Format

```
$$$ HR  $$ MIN  $$ SEC
                    RCS  SYSTEM 1 STATUS
                         OX TK 1              OX VLV
                         *********            * ***             ENG STATUS
HE TK 1           ISO    ****$$$ PSI******      X *********** 1 ON    8 ON
*********         VLV    *  *$$$ PCT*         *****    ****   2 OFF  9 OFF
*$$$  DG*         ****   *  *$$$ DG *                  *0**   3 OFF 10 OFF
*$$$ PSI******    X***** *  *********                  ****   4 ON  11 OFF
*********         ****   *                    FU VLV   XFD    5 OFF 12 OFF
                         *  *********         *****           6 OFF 13 OFF
                         *  *  $$$ PSI******   X ************7 OFF 14 OFF
                         ***   $$$ PCT*       *****    ****
                           *   $$$ DG *                *0**
                           ************                ****
                           FU TK 1                     XFD
```

Figure 4.5-6.   Typical RCS System Status Format

B. Fixed Data Storage Estimates

Two different methods were used in estimating the software storage required for the RCS/OMS consumables management modules. The first method was to estimate the software required for performing the operations in the algorithms for the Evaluation, Monitoring, and Constraints Modules. The second method was to use actual storage required for similar existing programs; this method was used to arrive at the Consumables Prediction Module sizing estimate.

4.6 PAYLOADS CONSUMABLES MANAGEMENT

An additional area of Shuttle consumables management which was investigated was the requirement for consumables management support for Shuttle payloads. At this time, no requirements relative to payloads support has been found that would impose special requirements on the consumables management system.

Indications are that some payloads will require Shuttle subsystems support for providing such things as electrical power and atmospheric revitalization. The consumables management software would be required to account for the consumables usage resulting from such support and simply treat it as an additional load on the consumables subsystems. However, no requirement is evident which would require consumables management capability beyond that which is presently proposed.

Table 4.5-1 RCS/OMS Consumables Management Software Sizing Estimates

MODULE	FIXED STORAGE (words)	DYNAMIC STORAGE (words)
Evaluation	170	400
Constraint	50	-
Monitoring	270	-
Consumable Prediction	1600	500 Input Event Timeline 200 Output Data 1000 Words in Scratch Memory

5. REFERENCES

1. L. W. Neel, "First Quarterly Progress Report for Contract NAS 9-12944", 10 November 1972.

2. P. J. Graf, "Shuttle Consumables Management Concept", TRW Letter 6531.10-73-51, 16 May 1973.

3. L. W. Neel, "Second Quarterly Progress Report for Contract NAS 9-12944", 8 March 1973.

4. H. A. Herwig, "Software/Crew Display Interface Definition for Onboard Consumable Management", TRW Letter 6530.4-044, 26 July 1973.

5. T. E. Daly, "Guide to Computer Sizing", TRW IOC 10-7100.13-170, 23 July 1970.

6. F. E. Bupp, "Development of a Zero-G Gauging System", TRW No. 16740-6000-RU-00, January 1973.

7. R. A. Kaminskas and D. J. Malone, "Final Report on Development of Isothermal RIGS, Contract NAS 8-28574", 9 April 1973.

8. R. K. M. Seto, "Apollo 15 Mission CSM 112 Cryogenic Storage System Postflight Analysis Report", TRW No. 17618-H234-R0-00, November 1971.

APPENDIX A

SUBSYSTEM INSTRUMENTATION

It does not appear at this time that the proposed Shuttle consumables management system will impose any unique instrumentation requirements, and those which appeared in preliminary instrumentation lists will suffice. However, since the measurement method employed to monitor those parameters required in consumables management will definitely affect both the computational techniques and the overall accuracy of the consumables management system, some investigation was conducted to determine the instrumentation characteristics which are appropriate for each of the consumables included in the proposed system.

It should be emphasized that the factors discussed in this section are not to be construed as proposed design requirements since this study was only concerned with defining functional requirements. However, in the course of the study, data were accumulated which, for information purposes, will be presented and briefly discussed. A comprehensive study of instrumentation techniques was not performed, but since quantity gauging is the area of instrumentation most pertinent to consumables management, several quantity gauging systems were investigated.

A summary of gauging system characteristics reviewed under this study is presented in Table A-1. Table A-2 shows applicability of some gauging techniques. The following discussions provide insight into the various methods available for quantity gauging.

PVT Gauging

Quantity gauging performed by calculating quantity from measured values of pressure and temperature has been employed for numerous space applications. A configuration similar to that shown in Figure A-1 is used where a gas such as helium is used to pressurize the consumable tank thus providing expulsion under zero-g conditions. The PVT gauging method uses the measured value of pressurant temperature and pressure and known volume of

Table A-1. Quantity Gauging Techniques

Pressure-Temperature Gauge: (PVT)

1. Poor accuracy. Accuracy range $\approx$ 3%-6%.
2. Good for o-g measurements.
3. Measurement of pressure and temperature requires calculation to determine quantity.
4. Proven design. Used on previous space vehicles.
5. Light weight. Weight $<$ 2 pounds per tank.
6. Installation requires pressurant tank penetrations.

Nuclear Gauge:

1. Very accurate. Accuracy range $\approx$ 0.35%-0.75%.
2. Good for o-g measurements.
3. Insensitive to stratification of cryogenics.
4. No tank penetration required for installation.
5. Designed and tested. No prior operational use.
6. Not light weight. Weight depends on exact configuration. Weight $\approx$ 20 pounds per tank for 4 source/detector system.
7. Combination of tank size and consumable density limits applicability of technique.

Gas Density-Volume Gauge: (ρV-T Configuration)

1. Very accurate. Accuracy $\approx$ 1%.
2. Good for o-g measurements.
3. Light weight. Weight $\approx$ 2-3 pounds per tank.
4. Use with bladder or bladderless consumable tank.
5. Designed and tested. No prior operational use.
6. Penetration of both consumable and pressurant tanks required for installation.

Resonant Infrasonic Gauging: (RIGS)

1. Good accuracy. Accuracy $\approx$ 1%.
2. Good for o-g measurements.
3. Use with bladder or bladderless tanks.
4. No restriction on tank shape or size.
5. May operate with vented tanks.
6. Use for gauging cryogenics and liquids (with exception of liquid hydrogen).
7. Requires tank penetration for installation.
8. Has mechanical moving parts.
9. Designed and tested. No prior operational use.

Capacitance Gauge:

1. Good accuracy attainable. Accuracy range $\approx$ 1%-3% (Better accuracy increases cost.)
2. Not useful for o-g measurement of liquids.
3. Not useful for measurement of cryogenics if stratification exists.
4. Proven design. Used on previous space programs.
5. Not light weight - exact weight depends on configuration.
6. Requires tank penetration for installation.

Gas Density-Volume Gauge: (ρV-ρV Configuration)

1. Very accurate. Accuracy $\approx$ 0.5%.
2. Good for o-g measurements.
3. Light weight. Weight $\approx$ 2-3 pounds per tank.
4. Requires bladder in consumable tank.
5. Designed and tested. No prior operational use.
6. Penetration of both consumable and pressurant tanks required for installation.

Gas Density-Volume Gauge: (ρV Configuration)

1. Good accuracy. Accuracy $\approx$ 2%.
2. Good for o-g measurements.
3. Light weight. Weight $\approx$ 2 pounds per tank.
4. Use with bladder or bladderless consumable tank.
5. Designed and tested. No prior operational use.
6. Penetration of pressurant tank required for installation.

Radio Frequency Gauging: (RF)

1. Good accuracy. Estimated accuracy $\approx$ 1%-2%.
2. Good for o-g measurements.
3. Not good for consumables with high dielectric constant.
4. Requires tank penetration for installation.
5. Not developed sufficiently to judge utility for various consumables.

Liquid Level Detector:

1. Good sensor accuracy. Factors such as geometric placement of sensors and tank stretch limit accuracy.
2. Discontinuous measurement. Requires calculation and estimation technique to obtain continuous quantity indication.
3. Not good for o-g.
4. Require tank penetrations for installation.
5. Light weight sensors, but multiple sensors and associated wiring results in significant gauging system weight.
6. Proven design. Used on previous booster vehicles.
7. Useful only for liquid gauging.

Table A-2. Applicable Shuttle Gauging Techniques

Consumable	Applicable Gauging Technique for Consumables Management	Comments
MPS/ET Liquid Oxygen and Liquid Hydrogen	Liquid Level Detectors Nuclear Gauging RIGS RF	1. No present requirement for gauging for consumables management. 2. Continuous gauging may be useful for future applications if boost operational procedures require consumables management.
OMS Nitrogen Tetroxide and Monomethylhydrazine	PVT ρV-T ρV Nuclear Gauging Capacitance Gauge	1. PVT is questionable because of accuracy. 2. ρV techniques are more feasible than PVT because of better accuracy attainable. 3. Higher accuracy techniques will reduce allocation of unuseable consumable quantity. 4. o-g gauging is needed to perform consumables management continuous monitoring function. 5. Nuclear gauging will provide o-g measurement and very good accuracy.
RCS Nitrogen Tetroxide and Monomethylhydrazine	PVT ρV-ρV ρV-T ρV Nuclear Gauge	1. o-g gauging is required. 2. Number of tanks makes Nuclear Gauging unattractive because of weight involved. 3. PVT is adequate. 4. ρV techniques are attractive because they provide better accuracy than PVT. 5. Higher accuracy techniques reduce allocation of unuseable quantity.
APU Hydrazine	PVT ρV-ρV ρV-T ρV Nuclear Gauge	1. PVT is adequate. 2. ρV techniques will provide better accuracy than PVT. 3. High accuracy is not essential for consumables management purposes. 4. o-g gauging is needed to perform consumables management continuous monitoring function.
FCCS Oxygen and Hydrogen	Capacitance Gauge Nuclear Gauge RF RIGS (oxygen only)	1. Nuclear gauging is attractive for accurate measurement regardless of state of consumables. 2. Capacitance gauge is useful only if some means is provided to assure adequate mixing of cryos.
ECLSS Nitrogen	PVT ρV Nuclear Gauge RF	1. PVT is adequate. 2. ρV technique will provide better accuracy than PVT.
ECLSS Ammonia	PVT ρV-ρV ρV-T ρV Nuclear Gauge Capacitance Gauge RF	1. PVT is adequate. 2. o-g gauging required. 3. ρV techniques will provide better accuracy than PVT.
ECLSS Water	Bladder Displacement Nuclear Gauge	1. Bladder displacement measurement is adequate for consumables management. 2. Poor measurement accuracy is acceptable. 3. o-g gauging is required.

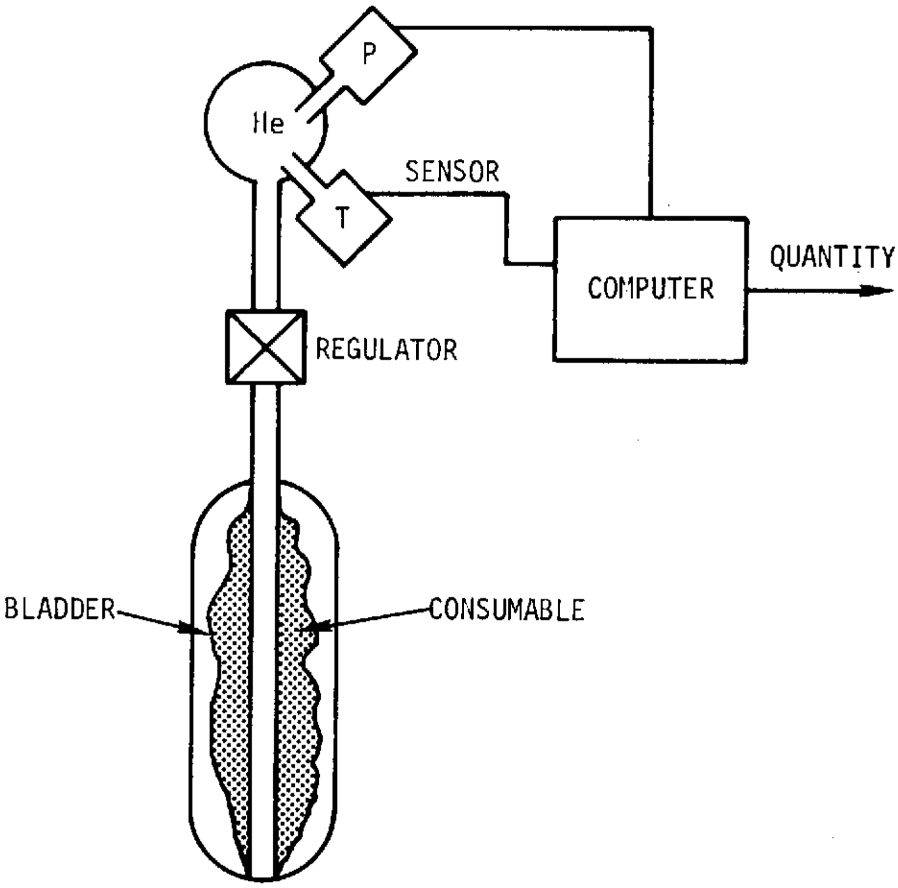


Figure A-1. PVT Gauging System Schematic Diagram the pressurant tank to determine pressurant density. Since the pressurant flows into the consumable tank cavity to compress the consumable mass within the bladder, the amount by which the gas density decreases within the pressurant tank is directly relatable to consumables mass remaining. This gauging method assumes that there is no gas leakage and that the measurement points are representative of gas conditions throughout the tank.

Numerous techniques have been employed to relate the pressurant temperature and pressure to consumable quantity remaining in the tank. The technique illustrated in Figure A-1 utilizes a computer to accomplish the calculations, but various analog methods are also used to perform the function.

PVT gauging has not proven to be very accurate; sensor accuracy of 3% is attainable, but operationally the gauging system accuracy has been observed to be closer to 6%. Consequently, undertainties in accurate knowledge of consumables quantity available results in what may be relatively large quantities of consumables being budgeted as unusable.

Gas Density-Volume Gauge

The gas density-volume, or ρV, gauge is similar to the PVT gauge except that, instead of measuring pressure and temperature separately to determine gas density, the ρV gauge measures gas density directly. Three different configurations using the ρV sensor are shown in Figure A-2 and are briefly compared as follows:

1. The ρV-ρV system has two ρV sensors, one in the pressurant tank and another in the propellant tank. This is the most accurate system; however, it is restricted to tanks using bladders because the propellant has to be kept out of contact with the ρV sensor.
2. The ρV-T uses a ρV sensor in the helium tank and a temperature measurement in the propellant tank. It assumes that the pressure in the propellant tank remains always constant. This system can be used with tanks with or without bladders.

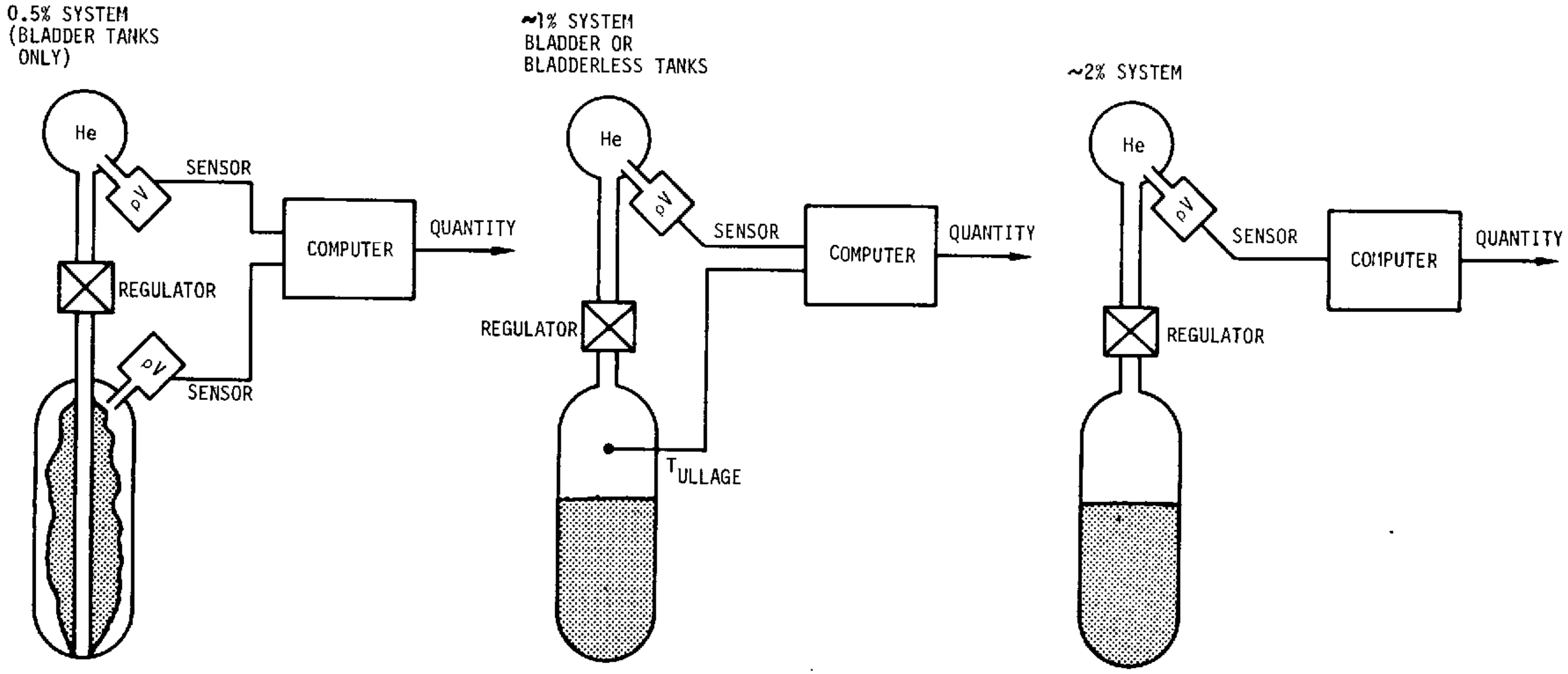


Figure A-2. ρV Gauging System Schematic Diagram.

3. The ρV system uses only one sensor in the helium tank. It assumes that the pressure and temperature in the propellant tank always remains constant. This is the least accurate configuration of the ρV gauge, but it is still considerably better than the PVT gauge.

The ρV sensor consists of a beta emitter radioisotope source and a semi-conductor radiation detector. Beta rays emitted from the source, which are partially absorbed by the gas, strike the detector. The number of betas striking the detector per unit time is related to the pressurant gas density which is in turn related to consumable quantity.

The ρV and PVT gauging systems are very comparable in terms of cost, weight, and principal of operation. However, the ρV system is significantly more accurate than the PVT technique as is illustrated by the relative comparison provided by Figure A-3.

Capacitance Gauge

The capacitance probe is a quantity gauging technique which has been utilized frequently on previous space programs. In its simplest form, a capacitance gauge is composed of two parallel plates in close proximity that are instrumented to measure capacitance, which is dependent on the dielectric constant of the substance between the plates. For a consumable of known dielectric characteristics, a measure of consumable quantity is obtained by the indicated capacitance since the consumables density between the plates produces a predictable capacitance indication.

Liquids are more easily measured by the capacitance probe since their presence provides distinctive changes in measured capacitance. However, liquid quantity measurements are not possible during zero-g operation as the liquid must be in a settled condition correctly aligned with the probe installation.

Sensor weight can become significant for larger tanks since the probe must extend the entire depth of the tank in order to provide gauging over the full range from empty to full conditions. In addition, supporting structure must be provided within the tank thus adding more weight to the installation.

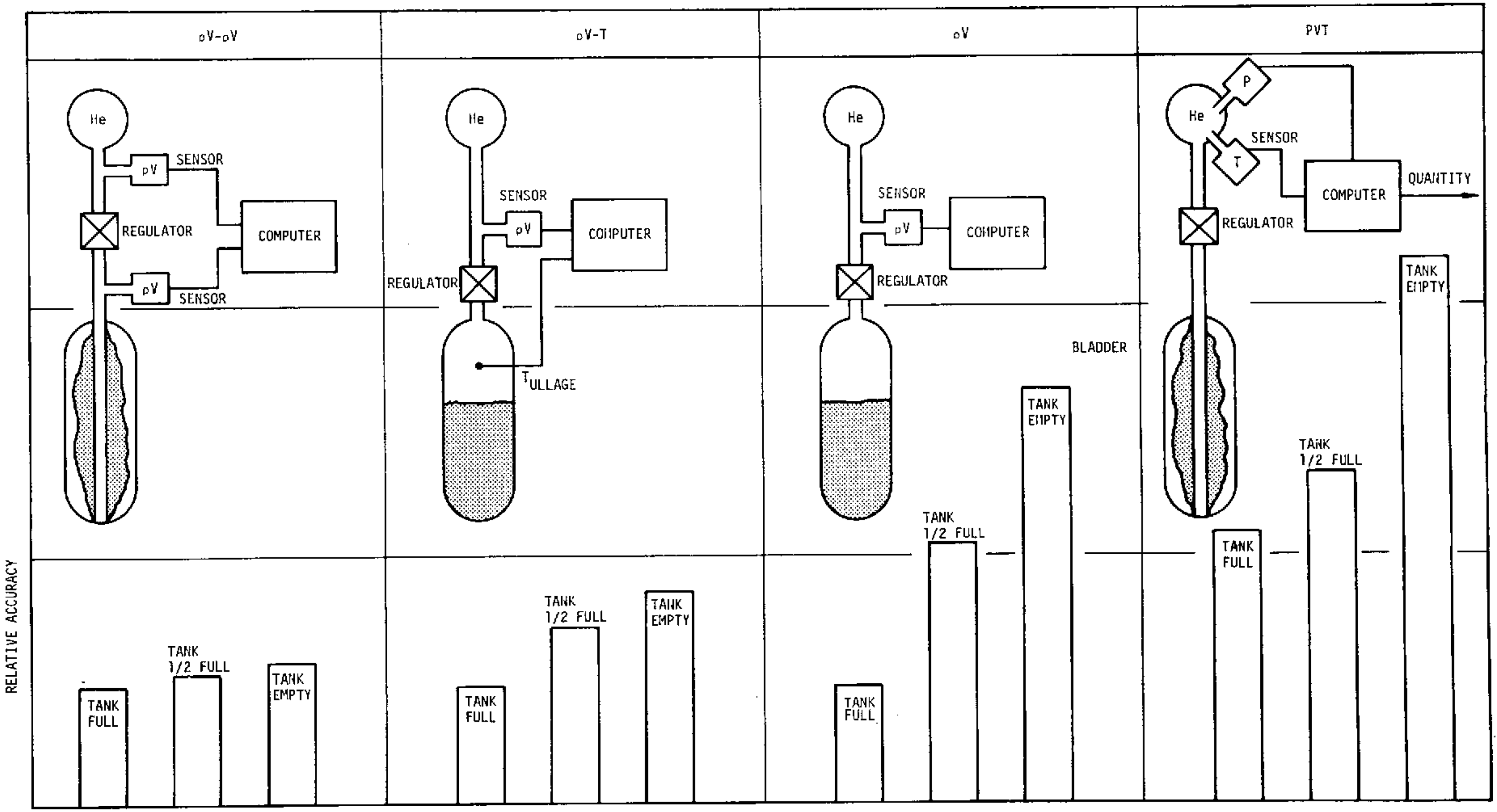


Figure A-3. Relative Accuracy Comparisons for ρV and PVT Gauging Techniques

Capacitance probes can provide very good accuracy if very precise techniques are employed in the basic design, assembly, installation, and calibration of the sensor. All of these factors cause significant increases in cost in order to obtain better accuracy.

Nuclear Gauge

A nucleonic gauge is composed of gamma-ray emitting radioisotope sources positioned on opposite sides of the tank from radiation detectors. Gamma rays that are emitted toward the detectors will be partially absorbed by the intervening consumable within the tank, and the amount of radiation reaching the detectors is then proportional to the mass of the consumable present in the tank.

Source-detector pairs may be mounted either external or internal to the tank. External mounting is advantageous in that no tank penetrations are required for installation thus reducing leak probability and simplifying maintenance. However, higher energy sources will be required to penetrate the tank walls which in turn requires larger source collimators thus causing increases in weight. Nucleonic gauging system weight is primarily controlled by the weight and number of the collimators which typically comprises 70-75% of the system weight.

Very good accuracy can be obtained by this technique and the accuracy is unaffected by either gravity conditions or consumable state. Therefore, cryogenics, which have been difficult to gauge because of stratification, may be accurately measured with liquid, gas, or slush present in the tank. Accuracies of less than 1% are attainable with this simple, reliable system.

One configuration of source-detector placement is shown in Figure A-4. The tank shape and size dictate the placement and number of source-detector pairs to achieve the best quantity measurement. A limitation in application of this gauging technique is that the gamma rays must not be completely absorbed before reaching the detectors. Therefore, the combined effect of long distance and a dense consumable between the source and detector is a limiting factor.

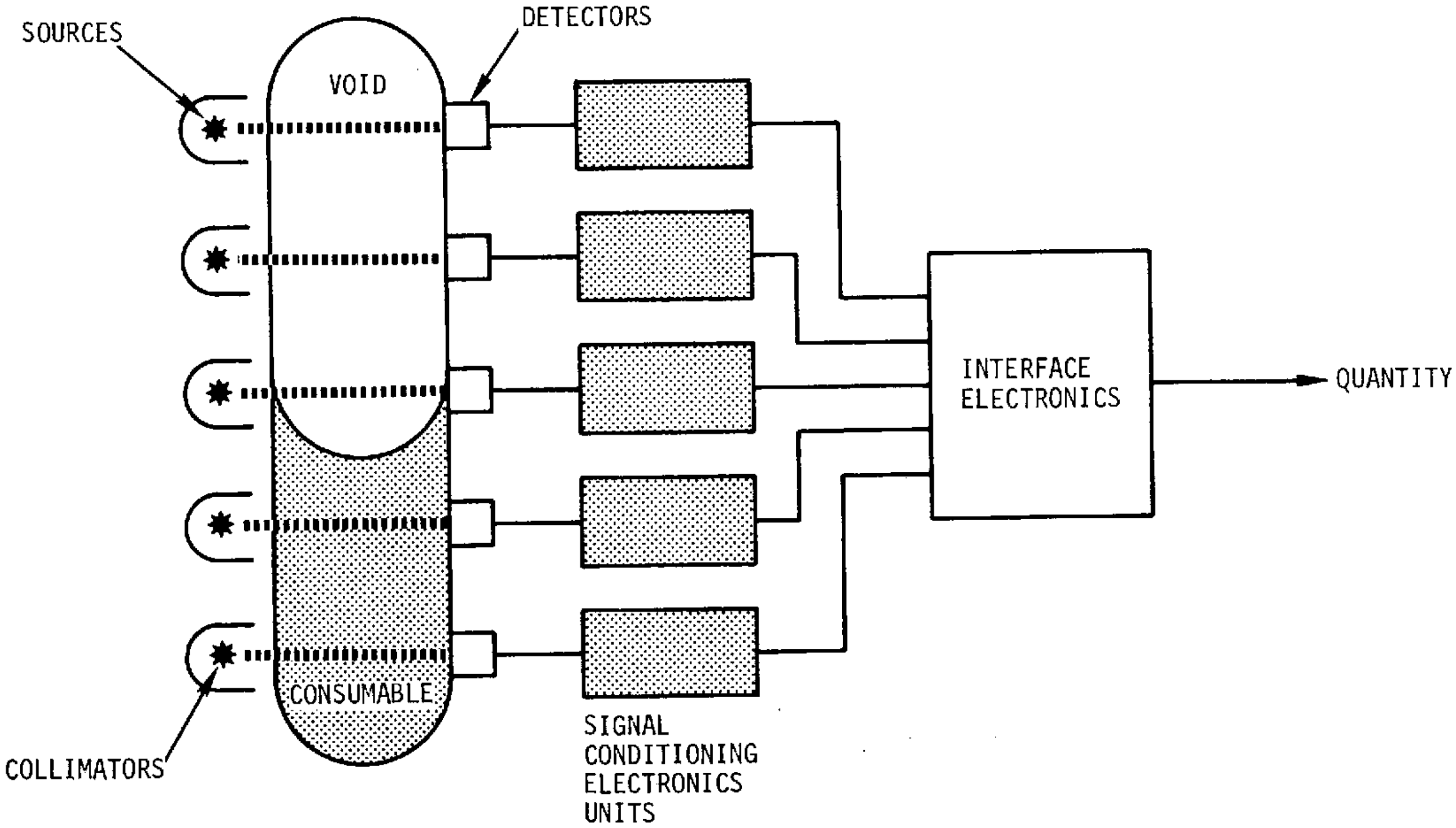


Figure A-4. Schematic Diagram of Nucleonic Gauging System.

Liquid Level Detectors

A number of different types of liquid level detectors are available to simply sense the presence or absence of a liquid consumable. A number of these detectors may be located at different levels within the tank and will, under gravity conditions, provide a gross indication of consumable quantity. This discontinuous quantity indication is of limited usefulness for consumables management purposes.

Accuracy of the liquid level detector is very good since it simply senses the presence or absence of a substance. However, significant inaccuracies can result from inaccurate geometric location of sensors and from tank distortion due to load and temperature effects.

Radio Frequency Gauging

RF gauging techniques have been developed, and subjected to limited testing, for determination of consumable quantity within a tank. The system operates by transmitting RF signals from a small antenna located inside the tank; the return signals establish resonances at various frequencies over a fixed frequency range. The number of resonances within the frequency range of interest will vary as the consumable quantity within the tank varies. Thus, a count of the resonances present at any time will provide an indication of consumable quantity remaining.

This gauging technique shows promise for future applications since it can produce good accuracy and the installation is very simple. Limitations exist in that some consumables have dielectric constants which result in poor ability to detect the resonances, but no evidence was found of adequate testing to accurately determine the exact limitations.

Resonant Infrasonic Gauging System (RIGS)

RIGS is a quantity gauging system for measuring liquids, with the exception of liquid hydrogen, under zero-g acceleration conditions. The system consists of a sensor which is attached to the tank and an electronic control unit. The sensor, which is shown schematically in Figure A-5, consists of a driver and a follower piston.

The driver piston frequency is varied to determine the frequency at which the follower piston is in resonance with the ullage gas volume of the tank. The resonant frequency, which normally ranges from 1-3 Hz, decreases as the consumable is depleted. Use of low frequency serves to assure that the ullage gas compression occurs in a nearly isothermal mode and that the pressure wave is transmitted through the propellant without significant attenuation.

The RIGS shows advantages over currently employed systems in that it will:

1) Operate under zero-g as well as acceleration
2) Operate with vented tanks
3) Gauge bladder or bladderless systems
4) Gauge any size or shape tanks
5) Operate with cryogenics (LH_2 excepted) as well as other liquids.

Tests have demonstrated gauging accuracy better than 1% is attainable using this technique.

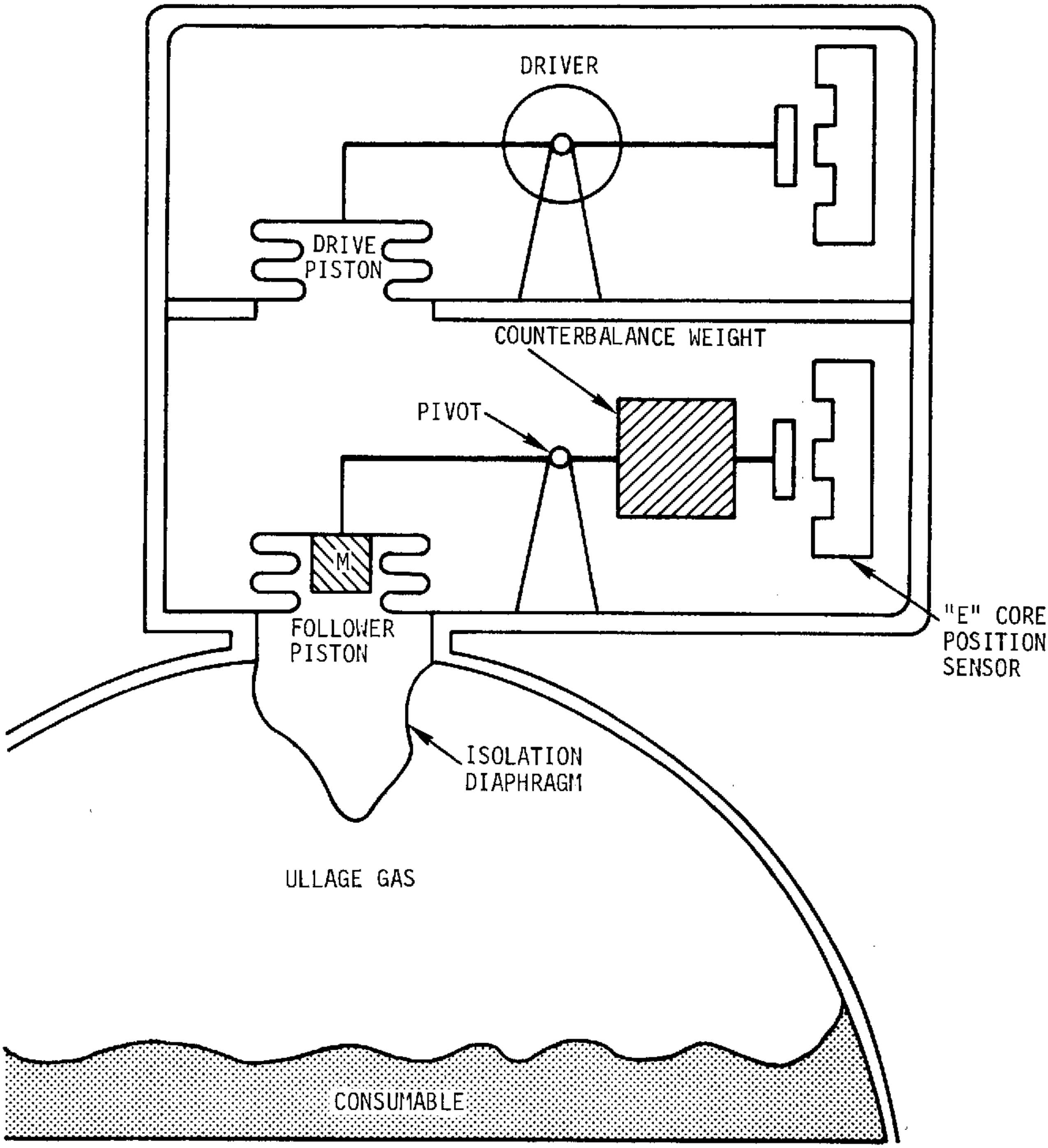


Figure A-5. RIGS Sensor Schematic Diagram

APPENDIX B

CONSUMABLES MANAGEMENT SYSTEM CRT DISPLAYS

The CRT display software should contribute to consumables management by providing display elements necessary for quick, thorough monitoring of the consumable subsystems in order to support both decision making processes and control action initiation. The CRT display system should also be designed to satisfy the basic requirements for an effective man/machine interface with the consumables subsystem by providing the operator with adequate real-time information of normal and alarm conditions.

The following CRT display capabilities are recommended to support the man/machine interface for the consumables management system proposed for the Shuttle.

Display Frame Retrieval - The CRT display frame retrieval software should provide the capability of retrieving display picture files from bulk storage. The display files should be structured into a fixed background segment and a dynamic time-varying segment. The fixed segment should contain only the display format background. The dynamic update software will provide the capability for updating the dynamic elements of the picture file.

Dynamic Update - The function of the dynamic update software should be to periodically update all dynamic elements for displays on the CRT screens. The dynamic elements are defined as those elements which vary with time such as instrumentation or computational data. The dynamic update software should be structured so that only those elements which differ from the last update will be revised. The information required by the dynamic update software should be contained in the dynamic segment of the picture files created by the display generation compiler.

Page Roll - The page roll capability allows the operator to page individual displays backward or forward. The roll capability is useful for examining tabular display formats.

CRT Display Data Entry - The CRT display data entry capability allows the console operator to change values of variables contained in core or the bulk storage data base via the keyboard or manual entry device (MED). This capability is required to support the consumable management concept of using realtime trend analysis results to modify or update parameters in the consumable calculation modules. The data entry software should incorporate reasonableness and data mode checks to help validate the data entries before insertion into the data base. All invalid entries should be denoted by an error message on the CRT screen. After completion of a data entry, the dynamic update software should provide a visual verification to the operator that the entry was accepted.

Figure B-1 illustrates the relationship of the consumables management software to the shuttle onboard computational facility. The Data Acquisition Control and Buffer Unit is utilized to provide the required interface between the subsystem data sensors and the computers. Contained within the computers is the consumable management software. Interfacing with the computers through MDM's and the Digital Electronic Unit are the Keyboard, CRT and Annunciators.

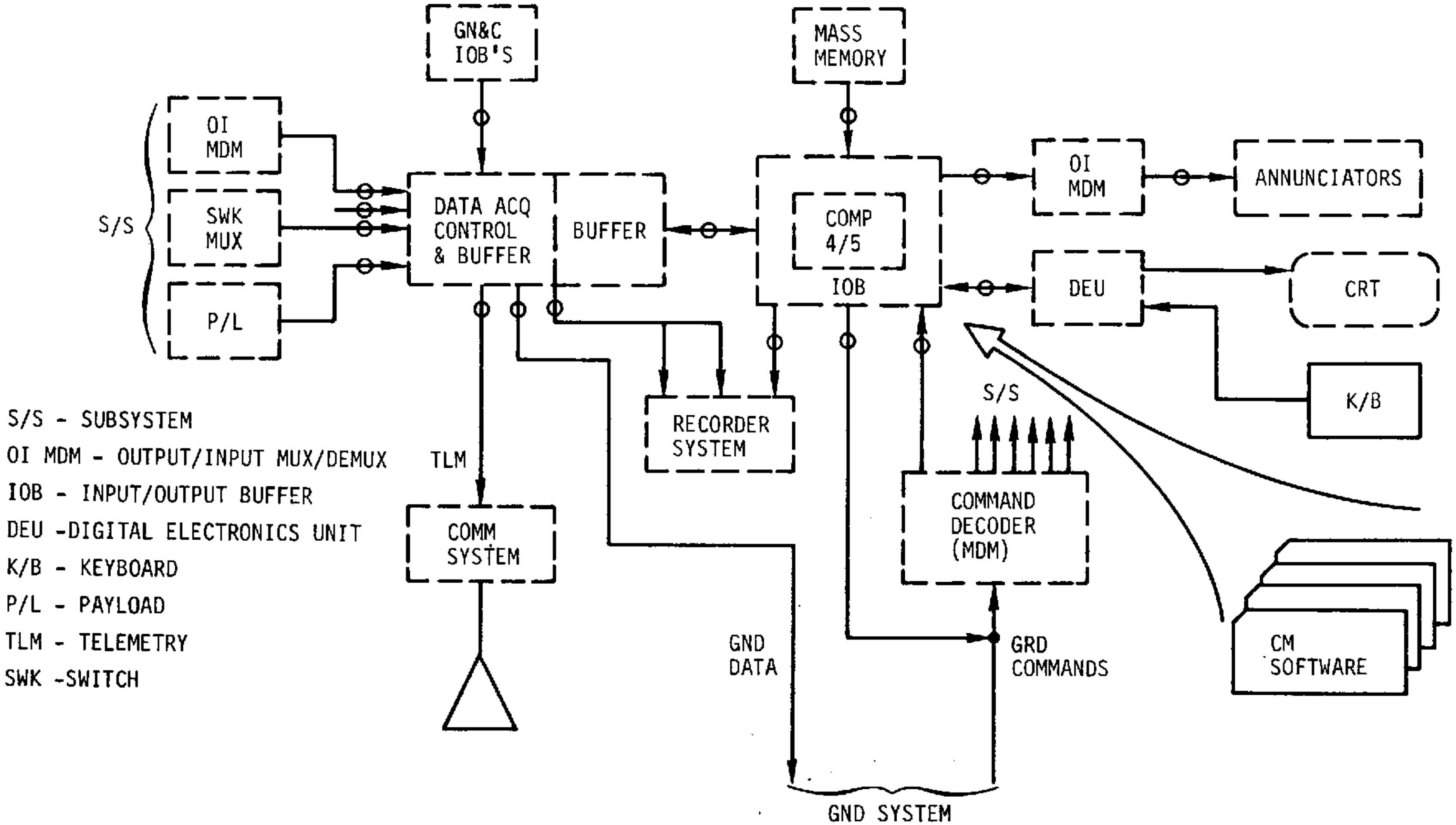


Figure B-1. Consumables Management Software Relationship to Shuttle Onboard Computation Facility

APPENDIX C

TREND ANALYSIS

Trend analysis is an important aspect of the evaluation and decision making elements of the consumables management process. Trend analysis can be defined as the storing and analysis of past performance data for the purpose of establishing performance tendencies which may be used in evaluating past system performance and in predicting future performance.

Trend analysis for consumables management can be divided into two techniques. The first is where the software, using stored usage data as a reference, calculates actual usage rates and projects end of mission reserves and redline violations. The second technique is to present the observed data on the CRT in order to allow the crew to predict future performance.

In the second method, it is almost always necessary to present the stored data in a form whereby all of the stored data can be viewed as a whole. Three forms of trending displays for the second method have been identified for possible use with the CRT or CRT display generator software and are discussed below.

It is assumed that only certain prespecified parameters are available for trending purposes and that not all trending parameters will be required at all times. Certain parameters will be identified, and sampling rates specified, premission so that trending data will be available from the start of the mission. However, the majority of the parameters will most likely be required at irregular intervals during the mission.

CRT Analog Trending - The CRT analog trending software should provide the ability to graphically display any selected consumables management variable on the CRT as a function of time. The operator should have complete flexibility in the selection of the variables to be plotted. The display utility is improved by providing automatic scaling of data for display; scale markings should be automatically generated on the axes.

The facility to modify the scales in the trend software should be available through manual data entry, and if manually chosen scales produce data out of limits, the operator should be notified by an appropriate warning.

CRT Digital Trending - The CRT digital trending software should be able to format several columns of tabular display at any one time. The trending interval should be specified via manual data entry with the same interval applying to all trended values appearing on the CRT screen. The display should be capable of being updated each cycle if required. The display format should use a data roll technique when the display field overflows. The technique consists of a "first in-first out" treatment of the data. As new trending data is displayed in the CRT, it should replace the oldest data displayed. This way only the latest data selected for trending is shown on the display screen.

Strip Chart Recording - Strip Chart Recording is mentioned as a possible option if the CRT graphical display capability proves of limited usefulness because of CRT resolution limitations. Essentially, the same software used in the formatting of trending data for the CRT can be used to drive similar displays on strip charts. This option would provide permanent recording of trended parameters which would be useful for post mission analysis as well as inflight analysis.

APPENDIX D

SOFTWARE SIZING ESTIMATION

One factor involved in establishing the viability of a system such as that proposed for Shuttle consumables management is demonstrating that software implementation is reasonable in terms of storage requirements. Accurate software sizing estimates are very difficult to make since many factors are involved such as specific machine and programming language features, algorithm definitions, programming techniques, and numbers of parameters and data points to be retained. Much of this information is non-existent at this stage of the consumables management software development. However, it is possible to make some preliminary sizing estimates, based largely on past software experience, which will serve to scope the software requirements for the consumables management software as it is presently envisioned. It should be emphasized that estimates only apply for the particular software implementation techniques assumed and for the operating conditions stated. Therefore, estimates should not be construed as being indicative of software for the operational consumables management software; the only intent in preparing the estimates is to show the relative comparisons, within each subsystem, of software required for the functional modules.

Prior to attempting to perform software sizing, it is necessary to define in some detail software functional descriptions which show the operations to be performed by the software. It is further required that algorithms be identified which are necessary to perform the functional operations. This preparation allows one to use one of the estimation techniques described below.

Routine Comparison - If existing programs can be identified which perform similar functions in a similar manner to that defined for the required program, sizing estimates may be obtained by comparison of the programs.

It is necessary to eliminate extraneous options, special input/output software, etc. in order to properly compare the computational software. Further, the sizing estimates obtained are only valid for the machine and programming language employed for the program selected.

Software Operations - Software sizing estimates based on software operations involves defining such things as equations, algebraic operations, standard subroutines, and logic manipulations required. Empirically derived factors are allowed for each of the subroutines and operations defined. In addition, allowance is made for temporary storage of variables and for scaling. The total of these estimates forms the estimate of the memory locations required.